AN EVALUATION OF THE EFFECTS OF BRINE ON A COMPACTED CLAY TILL LINER

RMD Report L-92

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AN EVALUATION OF THE EFFECTS OF BRINE
ON A COMPACTED CLAY TILL LINER

RESEARCH MANAGEMENT DIVISION
Alberta Environment

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AN EVALUATION OF THE EFFECTS OF BRINE ON A COMPACTED CLAY TILL LINER

by

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reviewed by

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for

RESEARCH MANAGEMENT DIVISION
Alberta Environment

RMD Report L-92

1986

EXECUTIVE SUMMARY

Compacted clay is not being considered for lining of brine ponds in Alberta because of the reported poor performance and adverse effects of brine solutions on the clay. This report addresses this concern through a laboratory test program on samples from the site of a compacted clay lined brine pond near Redwater, Alberta. A comprehensive literature review, case history evaluation and detailed laboratory testing program were carried out. Based on the results of this study, the following conclusions are drawn:

1. Controlling Factors: the effectiveness of compacted clay as a brine pond liner is controlled by the amount and type of clay minerals forming the liner and the pond operation conditions.
2. Clay - Brine Interaction: the process is complex and has been discussed in the literature, but can be summarized by a reduction in sample volume leading to cracking and opening of pore channels. These effects increase the permeability.
3. Reported Permeability Increase: the literature and several case records suggest that the permeability of a clay liner compacted with fresh water increases by about one order of magnitude when permeated with concentrated brine.
4. Observed Permeability Increase: laboratory tests on Redwater clay liner materials indicate that the permeability of "undisturbed" samples is about one order of magnitude higher than that of recompacted samples. Similarly, the effect of introducing brine to a sample compacted with a fresh water moulding fluid is an order of magnitude increase in permeability.
5. Field Versus Laboratory Permeability: the results of this study indicate that the field permeability is at least one order of magnitude higher than that

measured in the laboratory; this observation is consistent with similar studies reported in the literature.

6. Long-Term Effects of Brine: after 5 years of exposure to brine, samples of Redwater clay liner exhibited no appreciable changes to the morphology of clay minerals or the fabric of the aggregate (based on electron microscope test results).
7. Preconditioning by Brine Soaking: the effects of soaking samples in brine in the laboratory were negligible compared to other factors influencing permeability; however, crack formation in the field is an important factor controlling field performance which could not be modelled in the laboratory.
8. Design Studies Using Uncontaminated Samples: the laboratory test program of Redwater clay liner samples and uncontaminated samples from the site demonstrated that the latter can be successfully used in design studies to establish the effects on permeability of brine.
9. Implications for Design: the study indicated that the most critical factor controlling permeability of a compacted clay liner at a brine pond in Alberta is the adverse pond operating conditions. The main implication for design of future ponds is that if suitable liner protection measures are incorporated into the liner design, then the field performance can be better defined and seepage losses might be predicted with reasonable accuracy.

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ABSTRACT

A brine pond relining project undertaken for Procor Limited at the Redwater LPG storage facility provided an opportunity to collect samples of a clay liner for further study. This report presents the results of a study of the effects of brine on the properties of the clay liner. The study is somewhat unique in that field samples of a pond liner in operation for about five years were obtained for comparison with laboratory tests. The project addresses both the long-term (5 year) effects of brine on clay properties and our current ability to model field operating conditions in laboratory tests.

The study indicated that the interaction of brine solutions on clay minerals appears to be relatively rapid; the long term (5 year) effect of brine on clay was not significant in this study. Preconditioning of the liner materials by soaking in brine had a limited influence on the compacted permeability, but may be important in field situations by limiting crack formation when the clay shrinks. The study also demonstrated that the effects of a brine permeant can be reasonably modelled in the laboratory using natural, uncontaminated soil from the Redwater site (i.e., the common method of evaluation at the design stage).

The implications for brine pond design are that for materials with relatively small amounts of clay minerals, an order of magnitude increase in permeability over laboratory estimates should be expected in a brine environment. The adverse operating conditions at brine ponds is an important factor controlling field performance of compacted clay liners. However, with proper liner protection and possibly preconditioning through soaking in brine, compacted clay may be a suitable pond lining option at many sites.

ACKNOWLEDGEMENTS

We acknowledge the helpful advice given by Dr. T. Beukeboom, of Alberta Environment, who acted as overall project co-ordinator and liaison officer with the Komex project team. Authorization to proceed was given by Alberta Environment Contract No. 85-0407. The Research Management Division of Alberta Environment is acknowledged for supporting the study. Procor Limited is also gratefully acknowledged for granting permission to sample and test the materials underlying the recently rehabilitated brine pond at its Redwater LPG storage facility.

The project was co-ordinated by Mr. B.H. Conlin, formerly of Komex Consultants Ltd.,[1] with support in laboratory testing, literature review, and report preparation by Mr. W.N. Diddens, Mr. D. Lam, and Mr. F.B. Claridge, all of Komex. The project was initiated in the fall of 1984 and was substantially completed by April 1985.

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[1] Currently with Golder Associates, Vancouver, B.C.

1. INTRODUCTION

1.1 BACKGROUND

It is becoming a common practice in Alberta to line brine ponds with flexible polymeric membranes such as high density polyethylene (HDPE). Flexible polymeric membranes are often chosen because of the generally poor reported performance of liners composed of reworked, fine grained materials on site. A common assumption is that brine tends to shrink and crack the natural materials forming the pond liner,[1] rendering the liner unserviceable. The deterioration of natural materials in the presence of highly concentrated brine solutions has been observed at several locations in Alberta (e.g., Procor site and Imperial Oil site near Redwater, Alberta) and at other locations. Although this generalization is useful in evaluating the suitability of various liner materials, it could lead to the unjustified exclusion of certain natural materials for use as brine pond linings. Additionally, the unit cost of typical 80 mil (2 mm) HDPE can be twice the cost of compacting local materials to form a 1 m thick liner.

To evaluate the performance of liners, the seepage loss under a given hydraulic head (i.e., pond depth) should be compared, in addition to the permeability or hydraulic conductivity of the "liner" that forms a thin membrane in the pond bottom. Seepage loss in terms of velocity of flow, v, is related to permeability, k, after Darcy's Law:

$$v = ki$$

where i is the hydraulic gradient. The importance of both the gradient and permeability can be demonstrated by an example calculation. A compacted clay till with a permeability of 2×10^{-6} cm/sec under a hydraulic gradient of 0.75 will experience the same seepage loss as a flexible polymeric membrane with an effective permeability of 2×10^{-10} cm/sec (i.e., pinholes and poor quality seams that often occur in the field) under a hydraulic gradient of 7000, which corresponds to full head loss over a pond depth of 14 m and a membrane thickness of 2 mm (e.g., 80 mil HDPE). This simple example illustrates the importance of considering the site-specific hydraulics and hydrogeological conditions in evaluating liner performance. Further, a compacted clay liner might prove adequate in many situations regardless of any permeant-liner interactions that influence permeability.

---

[1] The term "pond liner" is used throughout this report to refer to the membrane of material in the pond bottom; the "liner" could also include the natural subsoils that effectively limit seepage lost through the membrane.

This report evaluates the permeability and clay-brine interactions of a compacted clay till liner material collected from a disused brine pond near Redwater, Alberta. The project includes a review of published literature and a laboratory testing program with the objective of addressing the following questions:

1. What is the long-term effect of brine leachate on compacted clay till liners?
2. Are there methods by which conditioning of natural clay liner materials can minimize shrinkage and degradation?
3. Can samples of uncontaminated natural soil be collected during the planning stages of a brine pond study and appropriately tested in the laboratory by introducing brine solutions to simulate long-term effects in the field?

1.2 CASE HISTORY STUDIED

The study utilizes performance case records and materials obtained at the site of a disused brine pond located near Redwater, Alberta. At this site, natural gas liquids (NGL) are stored in salt dome solution cavities and fluid levels in the storage caverns are controlled by displacing NGL with hypersaline brine solutions. The surface brine ponds serve as a holding facility for the brine solutions.

The pond was constructed by cut and fill methods and compaction of local clayey silt till materials to form a "liner" that was 0.5 m to 0.75 m thick. No surface cover or protection was placed on the exposed liner. The pond had been operated since 1978.

Perimeter monitoring wells were installed in the fall of 1979 and continuously monitored since that time. In 1983, the owner decided to reline the pond using HDPE. During the relining phase, the natural liner materials were excavated and disposed of on site. Block samples of the excavated natural liner were obtained for laboratory testing and evaluation as discussed in this report.

1.3 SCOPE OF STUDY

The study focuses on a laboratory evaluation of the effects of hypersaline brine leachate on the behaviour of compacted silty clay till materials. The report attempts to address the questions listed in Section 1.1 through a site-specific laboratory testing program and a general review of published literature on clay liner[1] - brine interaction.

The general characteristics of clay liner - brine interaction as reported in the literature are presented in Section 2 of this report to establish the major factors controlling changes in performance (and particularly hydraulic conductivity)[2] of clayey materials subjected to concentrated permeants of NaCl solutions. Having established the range of factors influencing behaviour and the reported trends in the literature, the testing program and results for the Redwater brine pond are discussed in Section 3. The test results are analysed and compared with the theoretical and observed trends as reported in the literature in Section 4, and the implications of the results for the evaluation of existing brine ponds or the design of a new brine pond are discussed in Section 5. Conclusions of the study and recommendations for further reseach are presented in Section 6.

---

[1] The term "clay liner" is used in a generic sense as many liner materials can have a small percentage of clay sized materials (i.e., smaller than 0.002 mm) and a variable clay mineralogy and still be referred to as clay liners.

[2] The terms "hydraulic conductivity" and "permeability" are used interchangeably and are considered synonymous throughout this report. It is recognized that "hydraulic conductivity" is the more technically correct term to use in this study; however, "permeability is the more frequent term utilized for simplicity.

2. REVIEW OF LITERATURE ON CLAY LINER - BRINE INTERACTION

2.1 GENERAL

A comprehensive literature review was conducted to establish the factors affecting the interaction between clay liners and brine solutions. The literature review included an extensive search of published material in libraries in Calgary, a computer-based literature search of published material, and a written survey of research institutions and individuals involved in related studies. This section summarizes the results of the literature survey and focuses on information pertinent to the type of material and brine solution at the Redwater brine pond; that is, a compacted clayey silt till exposed to hypersaline brine solutions.

2.2 FACTORS INFLUENCING CLAY LINER - BRINE INTERACTION

The most important factor controlling the performance of compacted clayey materials for use as brine pond liners is the hydraulic conductivity[1] (permeability) of the in-place material. An evaluation of liner performance also requires knowledge of the thickness of the compacted zone and hence the flow gradient which, when combined with the permeability, determines the flow rate of seepage lost from the pond. The literature review focuses mainly on the factors influencing permeability.

The in-situ hydraulic conductivity of fine grained soils (i.e., more than 20% by weight passing No. 200 sieve) is largely controlled by site geology. For example, seepage pathways may exist in the surface zone due to root holes, and bedding features, sand partings, and fissuring can occur in natural materials, particularly glacial till deposits. Thus, field estimates of hydraulic conductivity are preferred for design. Laboratory tests have the inherent problem of limited sample size and disturbance. However, laboratory tests offer the advantage that they can be performed under controlled conditions.

---

[1] For this report, the terms hydraulic conductivity and permeability are used interchangeably.

The sources of error in laboratory hydraulic conductivity tests are numerous. Olson and Daniel (1981), for example, identify the main sources of error and estimate the effect of each on test results as listed in Table 1. Olson and Daniel (1981) evaluated several case records and found that the ratio of hydraulic conductivity in the field to that measured in the laboratory was in the range of about 0.38 to as high as 64.0.

The state of saturation can have a marked influence on in situ permeability because unsaturated soils contain air pockets that block the passage of fluids through pore channels. Thus, partially saturated materials exhibit lower permeabilities than if the materials were completely saturated (e.g., measured values may be two to five times lower than for saturated conditions). It is common to assume that the ultimate field conditions tend toward complete saturation because the trapped air is eventually flushed through the material. The assumption of saturated flow conditions at the site studied in this report is a reasonable assumption because of the exposure time to brine, the considerable volume of seepage through the material (five years of operation), and the often high temperatures of the brine due to solar heating (temperatures up to 45°C measured in pond bottom), which tends to dissolve the trapped air. Therefore, the following discussions are based on a saturated flow condition.

For saturated flow conditions, there are three dominant factors that influence seepage under relatively low gradients (i.e., gradients between 1 and 10, where Darcy's Law, $v = ki$, would apply):

1. Characteristics of permeant - the viscosity, temperature, pressure, and density.
2. Soil properties - void space or porosity, distribution of void space, particle arrangement or fabric.
3. Soil and permeant interaction - ionic concentrations of permeant, interaction of permeant and clay mineral particles leading to swelling/shrinkage of material.

Each of these factors is discussed separately in sections 2.2.1 to 2.2.3.

Table 1. Sources of error in hydraulic conductivity tests performed in the laboratory on fine grained soils.[a]

Source of Error	Cause or Effect of Error	Method of Minimizing Effect of Error	Influence on Hydraulic Conductivity, K, Measurement
1. Nonrepresentative samples	Variability of deposit, tendency to select homogeneous zones	Through field investigation, develop accurate geological model	± one order of magnitude or more
2. Sample preparation	Voids, stress relief, fissures, smear zones, variation in molding water content	Carefully trim; apply stress to close fissures; use as large a specimen as possible; control moisture-density of compacted soils	± one order of magnitude or more
3. Sample placement in cell	Dispersion of fines, irregular cell wall contact leading to piping during test	Carefully place and tamp in cell; remove pebbles in trimmed sample; use cell constructed of transparent material (e.g., lucite); apply sufficient cell pressure in triaxial tests	± one order of magnitude or more
4. Flow direction	Sample generally oriented vertically, whereas horizontal flow may dominate in site	Orient laboratory specimen to model dominant flow direction in site	K_H/K_V may range from 1 to 10 or higher
5. Alterations in clay chemistry (permeant)	Leaching sample with distilled water, permeant with different chemical characteristics than in field	Where possible, use permeant with same chemistry as field, recycle fluids; use tap water rather than distilled water	± two orders of magnitude in extreme cases

continued . . .

Table 1. Continued.

Source of Error	Cause or Effect of Error	Method of Minimizing Effect of Error	Influence on Hydraulic Conductivity, K, Measurement
6. Growth of micro-organisms.	Clogging of flow channels by organic matter that grows in sample during prolonged tests	Use disinfectant in permeant if microorganisms would not grow naturally in field situation studied	± 8 to 50 times K for prolonged tests (measured values generally too low)
7. Air in sample	Attempted saturation of compacted sample	Apply backpressure to dissolve air into water; conduct test under a reasonably large pressure gradient (see Source of Error No. 9)	± 2 to 5 times K (measured values generally too low)
8. Equipment	Meniscus problems in capillary tubes, leaks, evaporation of permeant, volume changes of cell	Measure pressure drops instead of heads in capillary tubes; perform tests in well-constructed laboratory equipment; set up a dummy cell to measure evaporation and volume changes due to temperature fluctuations	0.3 to 3 times K depending on equipment problems
9. Excessive hydraulic gradients	If used to reduce testing time, and increase seepage quantity, may consolidate sample, cause piping	Use gradients as close as possible to field conditions, use falling head test	± 1 to 5 times K; may reduce K due to particle migration; limited influence for carefully run tests

continued . . .

Table 1. Concluded.

Source of Error	Cause or Effect of Error	Method of Minimizing Effect of Error	Influence on Hydraulic Conductivity, K, Measurement
10. Volume change of specimen due to stress change	Large gradients increase effective stresses in lower half of sample and may cause consolidation. Upper half experiences reduced effective stress (unless loaded) and may swell	Measure inflow and outflow, plot flow rate, q, versus time $t^{-1/2}$ and continue test until linear relationship is observed (steady state seepage condition)	Small, provided accurate measurements of sample swelling/compression are taken (generally 1 to 20 times too high)
11. Temperature	Viscosity changes of permeant	Peform tests at relevant temperature to field situation modelled	Viscosity decreases 3 % per °C rise; minor influence on K. (generally ± 0.5 to 1.5 times K)

[a] Source: Olson and Daniel (1981) and Gordon and Forrest (1981).

2.2.1 Characteristics of Permeant

Permeability varies inversely with the viscosity of the permeant. The viscosity of fresh water varies with temperature to the extent that if the value of permeability measured at 20°C is taken as 100%, then the value at 0°C would be 56% of this controlled value (and vice versa for increasing temperatures). The pressure and density of the permeant also affect permeability through the imposed gradients and gravity flow. The chemical characteristics of the permeant can interact with the soil particles (mainly clay minerals) and affect the flow characteristics as discussed in Section 2.2.3.

2.2.2 Soil Properties

The void space, distribution of voids, and particle arrangement or fabric are controlled by the particle size distribution of the material, the method of soil formation (compaction), moulding moisture content, and the consolidation or swelling behaviour under field stress conditions. The most important material property affecting the formation and distribution of void space is the percentage of fine particles, and particularly clay minerals, forming the aggregate.

The compaction characteristics of soils is a complex interaction between particle shear forces required to deform and reduce air content versus meniscus suction forces in the unsaturated phase tending to resist particle deformation by holding particles together. Various compaction methods can lead to different material densities and fabrics, as discussed by Lambe (1958), for example.

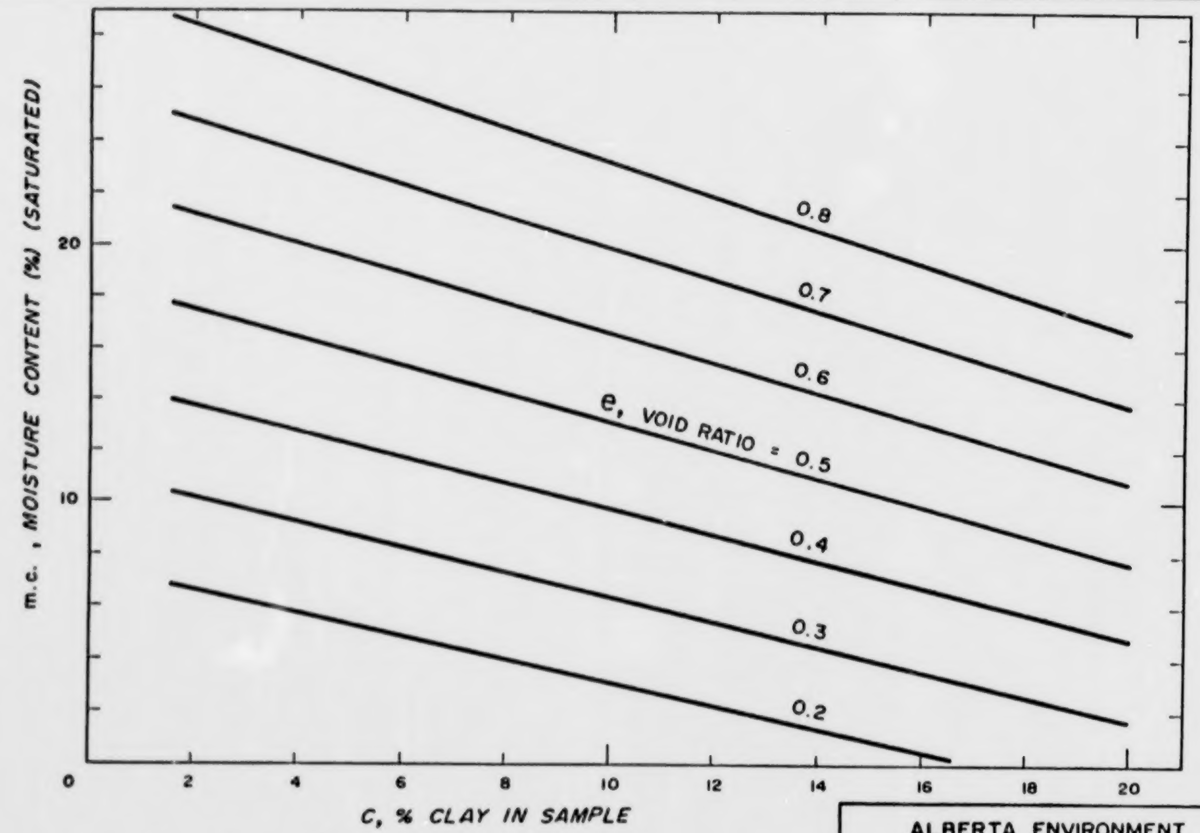
Particle shape and size distribution have a dominant effect on permeability as these factors control the development of void space and hence channels for the passage of permeant. For broadly graded material such as glacial tills containing sand, silt, and clay fractions, an important consideration is the percentage of clay minerals (i.e., illite, kaolinite or smectite[1]) versus non-clay minerals (such as quartz and feldspar). If one assumes that the moisture content of a mixture of grains of clay minerals and non-clay minerals is taken up by the clay mineral fraction, then the percentage of clay minerals necessary to fill the void space between non-clay mineral particles (and hence hold the granular particles apart) can be calculated using the approximate method presented by Mitchell (1976). An expression for the percentage of clay sized particles required to fill the void space of a mixed mineral grain arrangement is presented in Figure 1. The relationship plotted in Figure 1 indicates that, for example, at a moisture content of 16% (typical of the Redwater brine pond studied) and a void ratio of the compacted granular phase of about 0.5 to 0.6, between 5% and 10% clay sized particles would be required to fill the void space and hence, dominate behaviour.[2] For percentages of clay sized particles exceeding that required to fill the void space, the clay tends to coat the larger silt and sand size grains, holding the grains apart and thus having a dominant influence on the development of flow channels and hence on the permeability characteristics in the compacted state.

The permeability of compacted clays to water has been studied by researchers such as Daniel (1984) and Garcia-Bengochea et al. (1979), who indicate that the permeability of compacted clays is very much affected by the clay structure that develops during compaction. According to Lambe (1958), the behaviour and characteristics of a compacted clay can be explained in terms of a deformable aggregate soil model. After mixing with moulding water, the clay particles are grouped into aggregates. As a result, there are two

---

[1] Smectite is a generic term for a class of clay minerals that includes montmorillonite.

[2] The Redwater clay till has up to 30% clay sized particles and 9% to 13% clay minerals. The results of the scanning electron microscope (SEM) analysis presented in Section 8.4 illustrate the dominance of the clay minerals that coat larger silt sized particles.



$$m.c. = 100\left(1 - \frac{C}{100}\right)\frac{e}{2.68} - \frac{C}{2.75}$$

(after Mitchell 1976)

e = void ratio of granular fraction

G = specific gravity

assumed G = 2.68 (granular phase), 2.75 (clay minerals)

JOB No. 989

ALBERTA ENVIRONMENT

BRINE - CLAY LINER INTERACTION STUDY

CLAY CONTENT REQUIRED TO
DOMINATE INFLUENCE OF
MIXED GRAIN AGGREGATE

KOMEX	APPROVED 7-6C	DATE APR. '85	FIG. 1

Figure 1. Clay content required to dominate influence of mixed grain aggregate.

networks of pore space in the clay mass. The pore spaces within an aggregate are small (micro-pores or inter-cluster void space), whereas the pore spaces between the aggregates are relatively large (mega-pores or intra-cluster void space). For a given total void ratio, the hydraulic conductivity increases with a rise in the relative proportion of macro-pores. This is one reason why the hydraulic conductivity in clays does not correlate well with total porosity or void ratio (Garcia- Bengochea et al. 1979).

Two factors appear to dominate the compacted clay structure: one is the moulding moisture content and the other is the mode of compaction. When clay is compacted at a dry-of-optimum moisture content, the aggregates have a relatively high strength and are capable of resisting the compaction without much deformation. This results in a relatively high proportion of macro-pores and higher relative permeability. Clays compacted at a wet-of-optimum moisture content are nearly saturated and have lower shear strengths. Thus, the aggregates break down more readily during compaction. As a result, the macro-pores become compressed, and the relative permeability is lower than for the same sample compacted at a moisture content dry-of-optimum.

Mitchell et al. (1965) reported that clay compacted at a wet-of-optimum moisture content may have permeability values two or three orders of magnitude less than those compacted at a dry-of-optimum moisture content (see Figure 2). Such a variation in permeability may develop within relatively narrow ranges of moulding water content and density, particularly in the case of compaction at a wet-of-optimum moisture content condition.[1] These findings are consistent with those reported by Auvinet and Espinosa (1981).

The method of compaction also influences the permeability of clay compacted at a wet-of-optimum moisture content. Mitchell et al. (1965) concluded that clays compacted by kneading have lower

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[1] Samples were compacted at 2% to 4% wet of optimum for the test results discussed in this report.

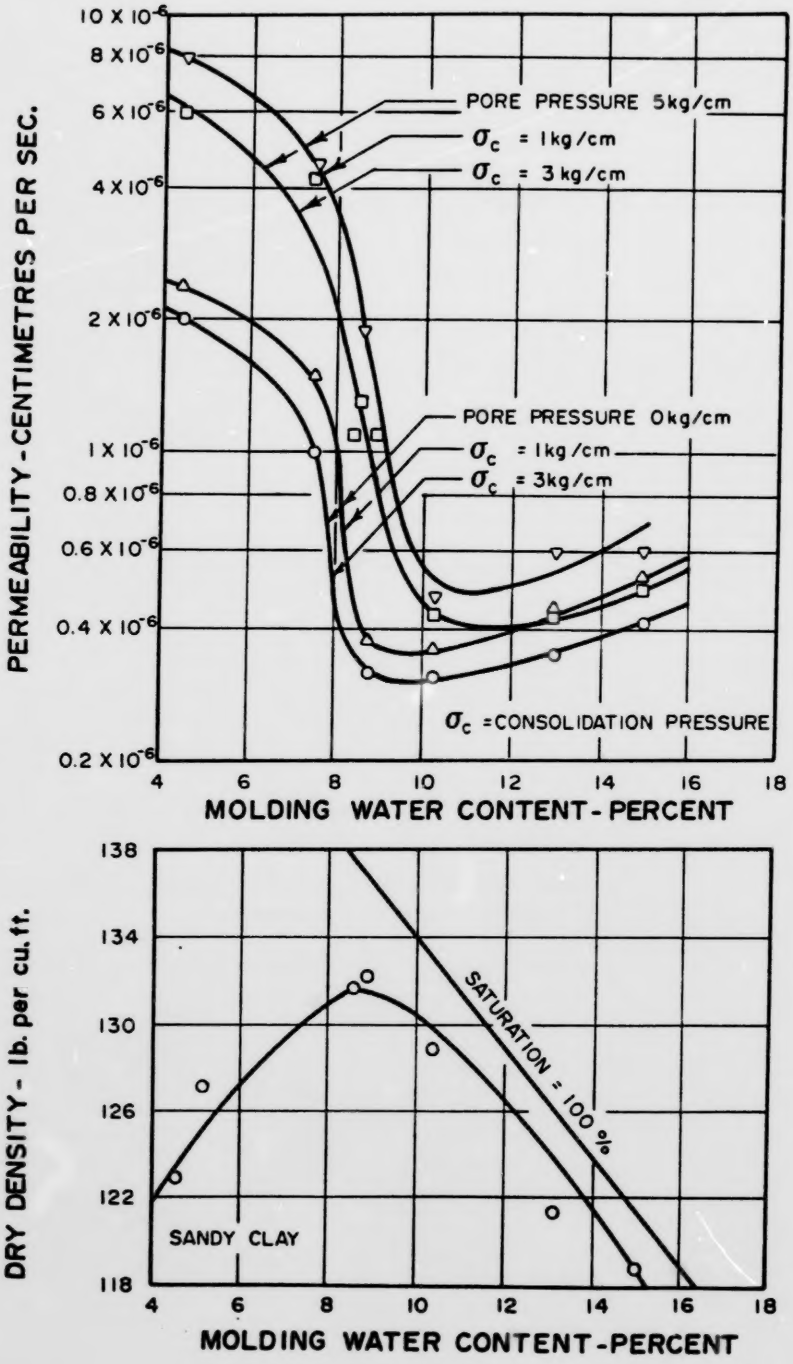

Figure 2. Effect of saturation using back pressure and consolidation pressure on permeability. (After Mitchell et al., 1965)

permeabilities than those compacted by static weight. The lower values are explained by the more dispersed structure associated with kneading compaction[1].

2.2.3 Permeant - Soil Interaction

The interaction between the permeant and soil particles is dominated by the clay mineral fraction (as compared with clay sized fraction passing 0.002 mm) because these particles have large surface areas, a net negative charge on the surface, and a layer of bound water surrounding the particles. Sand and silt sized granular particles composed of quartz and feldspar, for example, are relatively inert and do not interact with brine permeants of varying ionic concentration. The larger sand and silt sized particles could interact with acidic or alkaline permeants, but these leachates are not considered in this study. This study is focused on concentrated NaCl brine, referred to as a salt solution throughout this report.

A brief description of clay mineralogy is provided in Section 8.1 for reference purposes. However, it can be stated that the influence of brine on the clay minerals is of increasing importance for: kaolinite, illite, and smectite. The physical - chemical characteristics that affect the clay mineral behaviour (i.e., volume change characteristics) include changes in the thickness of the bound layer around the particle due to clay particle attraction, cation hydration, and/or osmotic processes as described by Coia (1981), for example. Changes in the double layer thickness can lead to a reduction (or increase) in pore space by shrinkage (or swelling) of clay minerals. As the double layer thickness shrinks, the decrease in volume of the sample could lead to crack formation. Additionally, the changes in the bound layer can lead to a rearrangement of particles and hence to a change in fabric. Further, breaking of inter-layer bonding can lead to particle mobility and dispersion. Dispersion can result in the migration of clay particles to plug smaller pores and hence reduce permeability or, depending on particle gradation and clay content, a loss of particles through larger openings (e.g., cracks) and progressive erosion and piping, leading to a significant increase in overall permeability of the material.

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[1] Samples of Redwater clay till were compacted in 10 cm diameter moulds using a Standard Proctor compacting process.

2.3 PUBLISHED LABORATORY TEST RESULTS ON BRINE-CLAY INTERACTION

2.3.1 General

Literature on the effect of salt brines on compacted clay liners is scarce. Some recent research on the effect of highly concentrated brines on compacted clayey till from Alberta and clay soils from Ontario has been conducted by Hudec (1979) and Yanful (1982). Other more general research deals with the effects of relatively weak salt concentrations on volume change characteristics and permeability variations.

Reports by Hudec (1979), Yanful (1982) and others indicate that clays exposed to salt experience significant changes in their properties, as discussed below.

2.3.2 Effect of Salt on Clay Plasticity

The presence of salt electrolyte in the pore water can greatly affect the plasticity, activity, and hence the permeability of clays, as it changes the inter-particle forces and surface tension of the liquid medium (Yanful 1982). An increase in cation concentration, or cation valence, results in a reduction in the net repulsive forces between particles, causing less water to be retained in the soil structure and hence, a reduction of the plasticity. Yong and Warkentin (1975) found that an increase in the cation concentration resulted in an increase of the plastic limit, a decrease of the liquid limit, and a corresponding decrease in plasticity index. The influence of the electrolyte on the liquid limit is generally more pronounced than on the plastic limit.

Hudec (1979) studied the Atterberg limits of clay from the Imperial Oil Limited (IOL) brine pond near Redwater, Alberta.[1] He reported that the salt-treated clays became stiffer and contained less water at the liquid limit, and more water at the plastic limit, thus reducing the plasticity index, as shown in Table 2. Hudec indicates that the soil became more silty and lost its cohesion.

After studying ten clays from ten different locations in Ontario, Yanful (1982) confirmed Hudec's findings that the treatment of clay with brine generally results in a reduction in plasticity index and liquid limit.

The Prairie Farm Rehabilitation Administration (1979) also studied the effects of brine on the plasticity of bentonite and noted a marked reduction in the plasticity index and the liquid limit.

2.3.3 Compaction Characteristics

The addition of salt brine to a clayey material alters the moisture - density relationship of the soil through physio-chemical changes. The effect of this process on the compaction characteristics depends on the percentage of clay present, its mineralogy, the extent of soil aggregation, and the cation exchange complex.

Rel'tov and Yemolayeva (1977) studied the influence of sodium chloride (NaCl) and calcium chloride ($CaCl_2$) solutions on soil compaction. They noted that clayey soil moistened with 1.5 N (Normal) sodium chloride solution yielded a lower optimum moisture content and a higher dry density than when distilled water was used. However, treatment with calcium chloride produced the opposite effect (Figure 3). According to Rel'tov and Yemolayeva (1977), these observations can be explained by the different characteristics of the exchange reaction in soils salinized with NaCl and $CaCl_2$.

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[1] The IOL site is within 5 km of the site studied in this report.

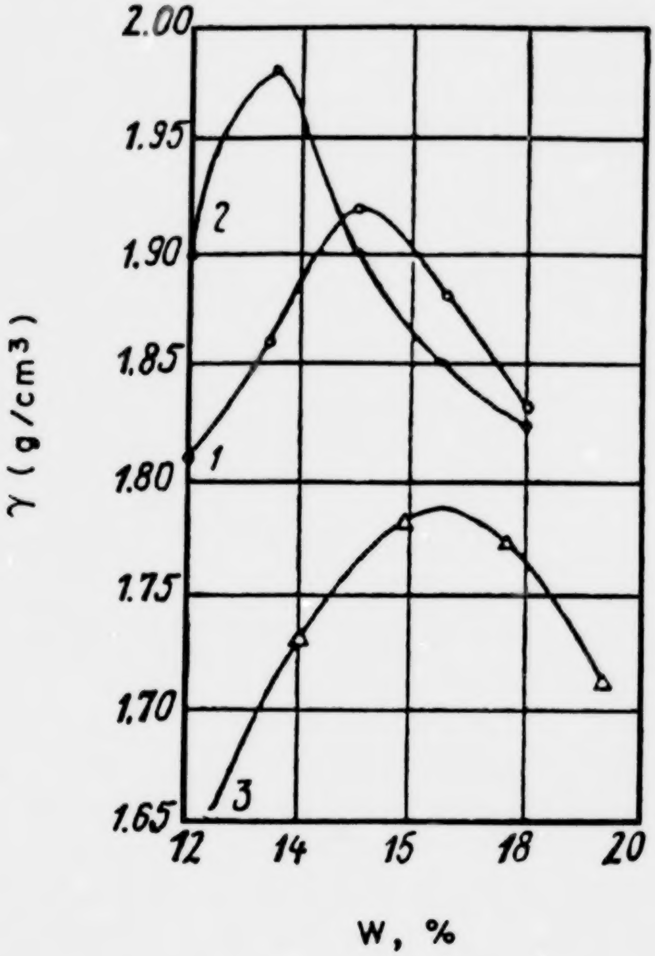
Table 2. Atterberg limits test results - IOL brine pond, Redwater, Alberta.[a]

Sample Type[b]	Liquid Limit	Plastic Limit	Plastic Index	Shrinkage Limit
Fresh Water				
1[c]	29.1	13.8	15.3	13.5
2	28.2	12.8	15.4	12.3
3	30.8	16.5	14.3	15.9
Brine (concentrated)				
1	23.7	16.1	7.6	25.3
2	25.9	14.1	11.8	22.6
3	24.8	17.3	7.5	23.1
Powdered Salt & Fresh Water				
1	26.0	15.8	10.2	25.8
2	25.4	14.2	11.2	24.7
3	24.8	15.5	8.4	25.7
Pond Wall	31.0	18.1	12.9	ND
Pond Bottom	30.6	17.2	13.4	ND

[a] Source: Hudec (1979).

[b] The clay samples were dried and re-wetted with the solutions indicated. In the case of powdered salt, the amount of salt used was calculated to give saturated solution when wetted with fresh water.

[c] Sample 1 - fresh water moulding
Sample 2 - brine moulding
Sample 3 - powdered salt and fresh water moulding



Legend

1 - moistened with distilled water
2 - the same with 1.5 N sodium chloride solution
3 - the same with 1 N calcium chloride solution

Figure 3. Dependence of the density, γ, on the moisture content, W, of Nurekskiy loam (Rel'tov and Yemolayeva, 1977).

In the case of NaCl, the composition of the cation complex changes by increasing sodium through displacement of calcium and magnesium. This exchange reaction causes the structural bonds inside the clay-water structure to weaken. As a result, the soil can be compacted to a higher density, with a corresponding decrease in the optimum moisture content.

The opposite reaction occurs when a clayey material is treated with calcium chloride. The net effect of this reaction is that the structure of the soil is strengthened and hence becomes more resistant to the breakdown of aggregates under the compactive effort. Thus, the density decreases and the optimum moisture content increases.

In Hudec's experiments with compaction of clay till materials from the IOL brine pond, he found that the use of a brine solution lowers the optimum moisture content, which supports Rel'tov and Yemolayeva's findings. However, no change in the compacted dry density was observed when compared to that of clay till compacted with fresh water moulding (Table 3). He attributes the lower moisture content of the brine-treated clay to the flocculated structure of the clay minerals and a thinner layer of adsorbed water around the clay particles. However, the observation of unchanged dry density and a shift in optimum moisture content is unconvincing and might be better explained by the presence of air in the voids. This phenomenon was not observed in the compaction tests performed during this study on similar materials from the Redwater area, where the density of brine treated material was found to increase. Yanful (1982) also observed a decrease in optimum moisture content and an increase in maximum dry density for Ontario clays after treatment with brine.

2.3.4 Shrinkage

As stated in Section 2.3.2, the presence of sufficient concentrations of salt in the pore water results in flocculation and

Table 3. Optimum compaction test results for clay liner materials from the IOL brine pond.[a]

Sample Type[b]	Unit Dry Weight[c] (g/cm^3)	Optimum Moisture Content (%)
Fresh Water		
1[d]	2.01	12.3
2	1.98	12.5
3	1.98	12.4
Brine (concentrated)		
1	1.98	11.5
2	1.98	10.9
3	1.97	11.7
Powdered Salt & Fresh Water		
1	2.03	11.4
2	1.96	11.0
3	1.95	11.2

[a] Source: Hudec (1979).

[b] Samples prepared as for Atterberg Limit Determinations.

[c] Standard Proctor - 3 lifts, 25 blows;
Assumed specific gravity of clay = 2.72

[d] Sample 1 - fresh water moulding
Sample 2 - brine moulding
Sample 3 - powdered salt and fresh water moulding

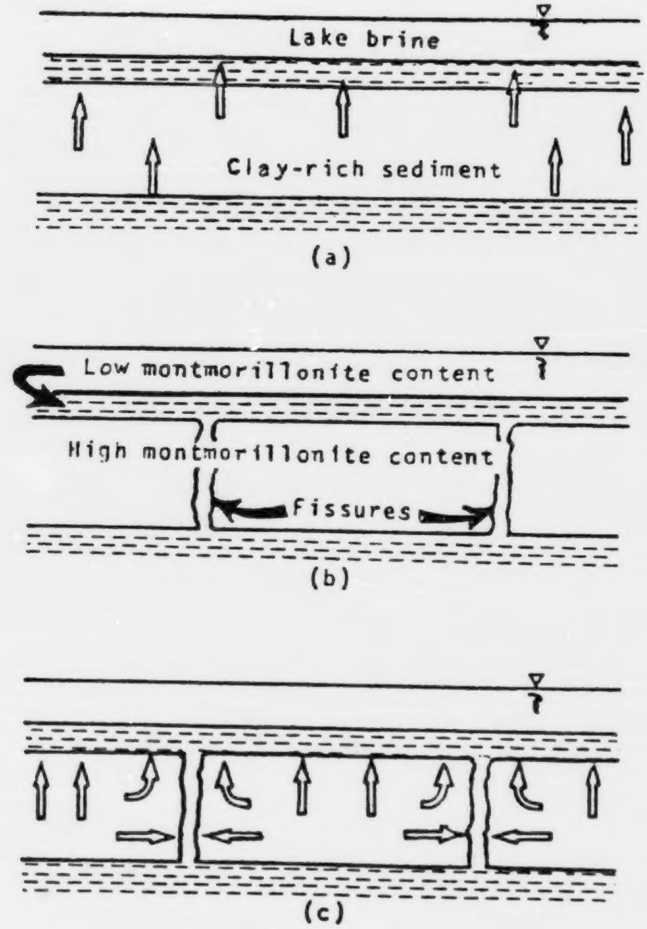


Figure 4. Proposed model for the development of fissures by osmotic desiccation. (After Turk, 1974)

an expulsion of water. Hence, when a compacted clay with fresh water moulding is submerged in a strong salt solution, it tends to shrink.

Turk (1974) attributed shrinkage of clay in a brine environment to osmotic desiccation due to a salinity gradient between the lower salt concentrations in the soil and the more saline brine solution. Using a conceptual membrane model of the osmotic process, he explained that when two fluids of different ionic strength are separated by a semi-permeable membrane, water molecules pass back and forth across the membrane, but the larger salt molecules cannot penetrate the barrier. However, the salt molecules take up space and interfere with the movement of the water molecules. As a result, a larger number of water molecules pass through the membrane in the direction of the higher salinity. Consequently, there is a net movement of water towards the side of higher salinity. Turk proposed a model for the development of fissures by osmotic desiccation, as shown in Figure 4.

Prof. K.W. Brown of Texas A & M University (telephone conversation with Mr. D. Folkes in January 1985) agrees that the osmotic process is a significant factor in the shrinkage observed in clays subjected to brine. In tests on intact clay, he reported shrinkage cracks developed at a spacing in the order of "a few inches." He also mentioned that bentonite (composed of a high percentage of smectite clay minerals) can withstand higher salt concentrations without developing fissures, due to the higher cation exchange capacity of the clay.

Hudec (1979), EBA (1978), and Yanful (1982) have reported the observation of syneresis (desiccation) cracks in clayey soil exposed to brine. Hudec (1979) placed fresh water clay patties in a brine solution and observed that the clay shrunk almost immediately, developing large, noticeable cracks. A linear shrinkage of 1.5% was recorded. Clay patties mixed with a hypersaline brine solution (i.e., "salt-treated" clay) were also tested for shrinkage when submerged in a brine solution. It was found that only minor cracks developed in the salt-treated clay. No cracking was observed when the salt-treated clay was submerged in fresh water.

Shrinkage in clay does not occur in a homogeneous manner. Yanful (1982) observed that cracks that developed in clays permeated with a brine solution were mostly horizontal. The horizontal nature of the cracks was attributed to the reorientation of the clay particles during compaction. He suggested that plate-like particles in clay tend to reorient themselves into a horizontal position during compaction. As the desiccation shrinkage of the clay caused by cation exchange is in a vertical direction (due to weak bonding between layers), cracks developed are therefore parallel to the plates. During an investigation of the effect of brine on the clay liner at the IOL brine pond, Hudec (1979) also observed horizontal cracks in the liner.

2.3.5 Permeability

The effect of brine on the permeability of compacted and natural clayey materials has been studied by several investigators, including Waldron and Constantin (1968); Rolfe and Alymore (1977); Dave and Klute (1977); Frenkel, Hadas, and Jury (1978); Frenkel, Geortzen, and Rhoades (1978); Hudec (1979); and Gordon and Forrest (1981).

The permeability of clay is greatly influenced by the type of electrolyte present in the clay-water system. As explained previously, this could lead to the expulsion of adsorbed water, and hence shrinkage. It has generally been recognized that flocculation increases soil permeability while dispersion tends to decrease it (Gordon and Forrest 1981).

The concentration of the electrolyte also has a significant influence on permeability (Frenkel et al. 1978; Dave and Klute 1977). McNeal and Coleman (1966) found that the permeability generally increases with increasing electrolyte concentrations or decreasing sodium adsorption ratio, SAR, and vice versa, as shown in Figure 5. This suggestion was supported by Hardcastle and Mitchell (1976), who reported that clay specimens permeated with solutions of

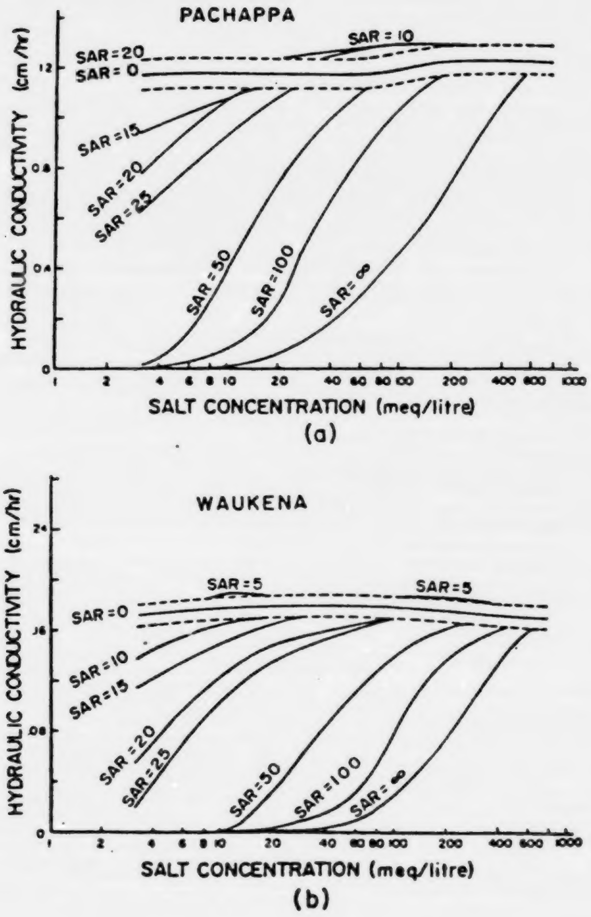


Figure 5. Hydraulic conductivity vs. salt concentration for (a) Pachappa sandy loam and (b) Waukena clay loam. (No detail is shown within 5% of the line for SAR = 0.) (After McNeal and Coleman, 1966)

successively lower electrolyte concentration showed a decrease in permeability (Figure 6).

McNeal and Coleman (1966) also noted that the effect on permeability of electrolyte concentration and sodium adsorption ratio was greater for soil high in 2:1 layer silicates,[1] such as illite and smectite. Soils that had the highest percentage of smectite exhibited the largest changes in permeability, while soils high in kaolinite or amorphous materials were somewhat insensitive to changes in solution composition. This is in agreement with Coia's (1981) findings that montmorillonite exhibited significant increases in permeability when the permeant was changed from water to 5 N NaOH, while that of kaolinite remained unchanged.

The permeability of clay is also affected by the valences of the cations. The replacement of sodium ions (monovalent) with calcium ions (divalent) renders the clay more pervious by giving it a crumbly structure (Lee 1941). Sodium treatment, which makes use of this principle, was commonly used as an agricultural process in the 1950s to improve the workability of a cohesive soil. Lee (1941) reported that the use of sodium ions to replace exchangeable calcium ions in a calcium-rich clay liner reduced its permeability.

On permeating brine through fresh water clayey silt till from the IOL brine pond liner, Hudec (1979) found that the permeability of the clay to the brine was five times greater than that of the same clay to a fresh water permeant (see Table 4; samples were 3 cm to 6 cm in height).

Yanful (1982) found that the permeability of a clay with fresh moulding water (a pure clay rather than a till mixture) is significantly increased when it is exposed to brine. His results indicated that the permeability of "fresh water clay" with a brine permeant is about 100 times greater than the same material when a fresh water permeant is used. He mentioned that fresh water clay

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[1] A brief description of clay mineralogy is provided in Section 8.1.

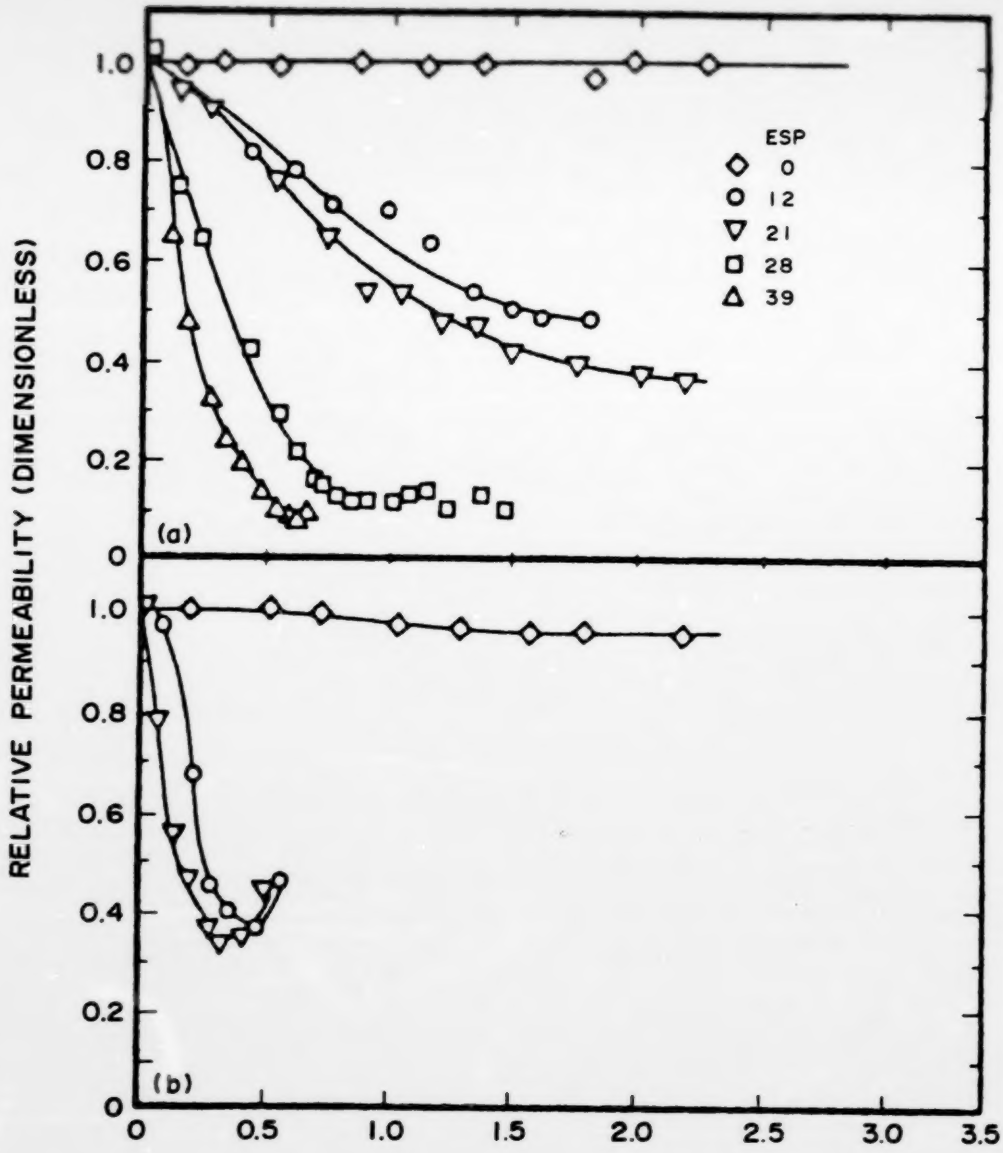

Figure 6. Effects on permeability of decreasing electrolyte concentrations: (a) to 0.01 N; (b) to 0.005 N. (After Hardcastle and Mitchell, 1976)

Table 4. Laboratory permeability test results on compacted samples of the IOL brine pond liner.[a]

Moulding Fluid	Sample Height (cm)	Permeant	Duration[b] of Test (hr)	Permeability, K x 10^{-6} cm/s Sample No.		
				1[c]	2	3
Fresh	6	fresh	120	0	0.04	1.00
Fresh	6	brine	196	0.11	0.12	0.52
Fresh	3	fresh	24	2.1	0.55	1.1
Fresh	3	brine	24	11.0	0.24	3.1
Fresh	3	brine	+24	12.6	0.28	3.0
Fresh	3	brine	+72	14.2	0.31	2.8
Salt	3	brine	48	0	2.8	7.3
Salt	3	brine	+42	12.4	3.2	7.8
Salt	3	brine	+72	16.3	2.9	6.7
------ sample recompacted -----						
Salt	3	brine	48	1.8	1.1	1.4
Salt	3	brine	+48	3.9	1.2	2.1

[a] Source: Hudec (1979).

[b] A plus sign in front of the hour indicates the continuation of the test under the same conditions.

[c] Sample 1 - fresh moulding
Sample 2 - brine moulding
Sample 3 - fresh water and powdered salt moulding

permeated with brine quickly developed syneresis cracks that were mostly horizontal. The extremely high permeability is due to the presence of extensive fractures. It should be noted, however, that Yanful's samples were very thin and hence small cracks could traverse the entire sample leading to unrealistic permeabilities.

Daniel (1984) reported a case history in which some undisturbed clay samples obtained from the clay liner of a brine pond in southern Texas were tested for permeability using brine permeant. After more than two weeks of permeation, it was found that the permeability values dropped during that period by an average factor of two. At the end of the tests, the permeabilities of the samples ranged from 1 x 10^{-7} cm/s to 4 x 10^{-7} cm/s. However, one month after the liner was put into service, significant leakage was detected.

It is understood that some North Dakota clays exhibited a marked increase in permeability due to flocculation when saturated with a solution of NaCl at concentrations above 0.5 N; whereas, dispersion and reduced permeability results from NaCl concentrations below approximately 0.5 N. When the brine saturated soil is exposed to rain and snowmelt, thus decreasing the Na concentration, the soil tends to disperse and becomes less permeable due to resultant clogging of pores by fines.

The effect on permeability of pretreating clayey till and a clay material with brine was investigated by Hudec (1979) and Yanful (1982), respectively. The permeability of a clayey till to brine is reduced by pretreating and remoulding the clay with brine, as shown in Table 4 (compare results for samples 1 versus 2 for a brine permeant). Yanful (1982) noted that the permeabilities of a brine-treated clay to brine and the fresh water clay to distilled water have the same order of magnitude, which suggests that the permeability of brine-treated clay to brine might be predicted from studying the permeability of the fresh water clay to distilled water.

The effect of test duration on the permeabilities of fresh water and brine treated clayey materials was studied by Hudec

(1979) and Yanful (1982). In general, Hudec (1979) found an initial increase in permeability with time, followed by a slight decrease for both the fresh water and brine-treated clays. Yanful (1982) concluded from his study that the permeability of fresh water clay to water is constant with time, while that of the treated sample to brine fluctuates to some degree, as illustrated in Figure 7.

2.4 CASE RECORDS

2.4.1 General

The following performance case records and results of laboratory testing are presented to illustrate the effect of concentrated salt brines on the interaction of compacted clayey materials. Some of the information was obtained from sites close to the Redwater brine pond, Alberta studied in this report. Other more general case records are for clayey materials as reported in the literature.

2.4.2 Imperial Oil Limited Brine Pond, Redwater, Alberta

The IOL brine pond located near Redwater is constructed of the same glacial till material as the Procor brine pond studied in this report. The surface brine storage pond was constructed in the summer of 1974 and, by 1977, leakage of brine was detected in 1977 and corrective measures were implemented.

The operational aspects of the pond are an important consideration for evaluation of performance. The following factors apply to both the IOL brine pond and the Procor brine pond:

1. The pond is full of brine near the end of the summer when underground storage of NGL or butane is at a peak. The pond is drawn down during the winter months as the stored gases are retrieved for sales. This fluctuating pond level exposes the side slopes and pond bottom to freezing temperatures during the winter months and drying during the summer months.
2. The hyper-saline brine tends to depress the freezing point of the pond fluid and the liner material.

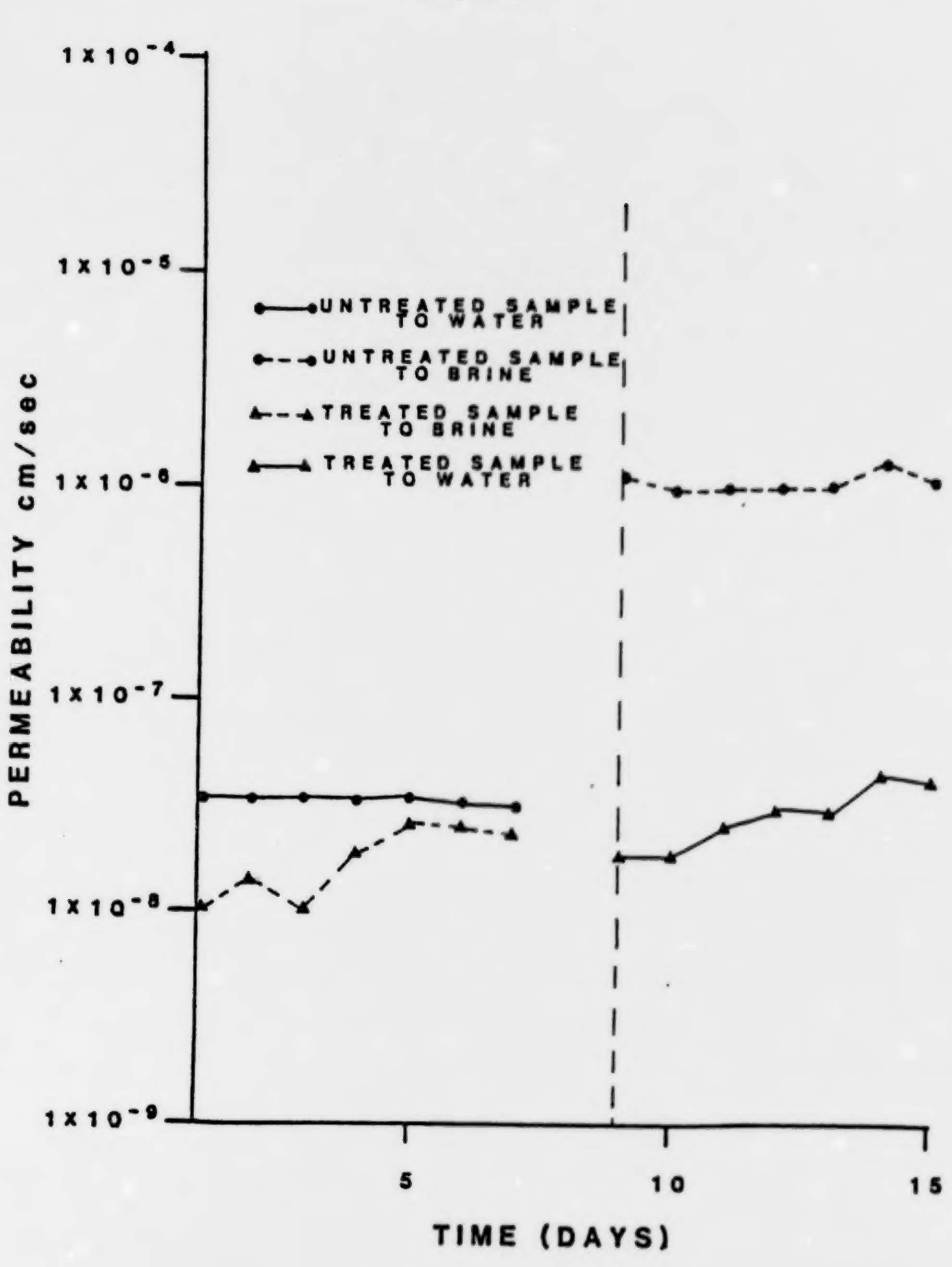

Figure 7. Changes in permeability with duration of test. (After Yanful, 1982)

Thus, the brine saturated clay liner can be "supercooled" below freezing without ice formation.

3. Make-up water, snowmelt, and precipitation entering the pond floats on the surface of the concentrated brine. This layer of fresh water has two effects: first, the sideslopes of the pond are subject to varying concentrations of brine and fresh water as the pond level fluctuates; and second, the concentrated brine can act as a solar collector during the summer months to heat the brine and hence, the clay liner.
4. Fluctuating pond levels tend to create cyclic wetting and drying of the clay lined materials forming the pond sideslopes.

An investigation of the brine leakage from the pond, including an in situ investigation program and laboratory testing of the liner, was conducted by EBA Engineering Consultants Ltd. (EBA) in 1978. The purpose of the investigation was to evaluate the cause of the brine leakage and make recommendations for relining the pond. A laboratory testing program was conducted on samples of the clayey silt till forming the pond liner, which had an average gradation of about 2% gravel, 34% sand, 43% silt, and 21% clay sized particles. The average Atterberg Limits of samples taken for laboratory testing were a liquid limit of 28%, a plastic limit of 16%, and a plasticity index of 12%. The in-place moisture content ranged from about 10% to 14%.

X-ray diffraction analysis of the clay fraction was conducted as part of the overall testing program. There was no observable effect on the clay structure due to brine saturation. The maximum percentage of montmorillonite in the samples analysed ranged from 6% to 9% by weight. The results of the X-ray analysis are included as Table 5, which shows the relative proportions of montmorillonite, illite, and kaolinite in the clay fractions.

Laboratory permeability tests on both "undisturbed" and recompacted samples were conducted by EBA (1978). Tests were

Table 5. Results of X-ray diffraction analysis for the IOL brine pond liner.[a]

Sample No. Depth	M5 75 to 125 (mm)	M10 225 to 275 (mm)	M45 50 to 100 (mm)	M69 50 to 100 (mm)
% clay size	18	18	26	29
Spacing changes caused by sodium and calcium ions	none detected	none detected	none detected	none detected
Relative percentages of clay minerals				
Montmorillonite	40	40	25	30
Illite	40	35	45	45
Kaolinite	20	25	30	25
Maximum % montmorillonite	7	7	6-1/2	8-1/2

[a] Source: EBA (1978).

conducted in a triaxial cell with high back-pressure to ensure saturation. The sample height was 10 cm in all cases, with initial moisture contents ranging from 11% to 16% (i.e., wet-of-optimum). A brine fluid from the site was used as a permeant in all cases and in addition, the recompacted samples were followed by permeating with distilled water. The moulding water for all samples was the in situ pore fluid, which was brine-rich. The laboratory-determined permeabilities for "undisturbed" samples were in the range of 3 x 10^{-9} cm/s to 3 x 10^{-8} cm/s. The permeability of recompacted samples was an order of magnitude higher and, upon introduction of distilled water to the brine-saturated samples, the permeabilities decreased dramatically by up to one order of magnitude. The test results are summarized in Table 6.

An analysis of the seepage losses from the pond conducted by EBA (1978) determined that the 1.2 m thick lining on the sides and 0.91 m thick lining on the bottom of the pond had an overall effective field permeability of about 2.1 x 10^{-6} cm/s to 3.0 x 10^{-6} cm/s, which is significantly higher than the laboratory test data would suggest. The difference was attributed to the sample preparation method and the closure, in the laboratory tests, of fissures that were probably open in the field.

Three mechanisms that may have contributed to the cracking of the liner were suggested by EBA (1978), including:

- Differential settlement of the pond, leading to tensile strains and fracturing
- Desiccation on pond sideslopes due to wetting and drying cycles
- Physical - chemical shrinkage due to syneresis (shrinkage of compacted clay till following changes in the thickness of the bound water layer around clay minerals from heat and concentrated brine solutions)

Hudec (1979) also studied the IOL brine pond and developed a model of brine-clay interaction to evaluate performance. The effect of electrolyte concentration on the double layer potential adjacent to a clay particle is shown in Figure 8. The thickness of

Table 6. Summary of measured permeability values, IOL brine pond liner.[a]

Sample No.	Dry Density (pcf)	Moisture Content (%)	Permeability (cm/sec)
5	119.9	15.3	2.5×10^{-9}
13	117.3	14.4	1.1×10^{-8}
15	116.4	15.9	8.8×10^{-9}
16	120.2	14.5	3.7×10^{-8}
Compacted Sample (1)	109.8	14.7	1.3×10^{-6} to 4.0×10^{-8}
Compacted Sample (2)	113.0	11.1	2.5×10^{-7} to 9.0×10^{-8}

[a] Source: EBA (1978).

NOTE: Samples 5, 13, 15, and 16 are undisturbed core samples from the in situ liner. Compacted samples (1) and (2) were taken from the liner and recompacted in the lab.

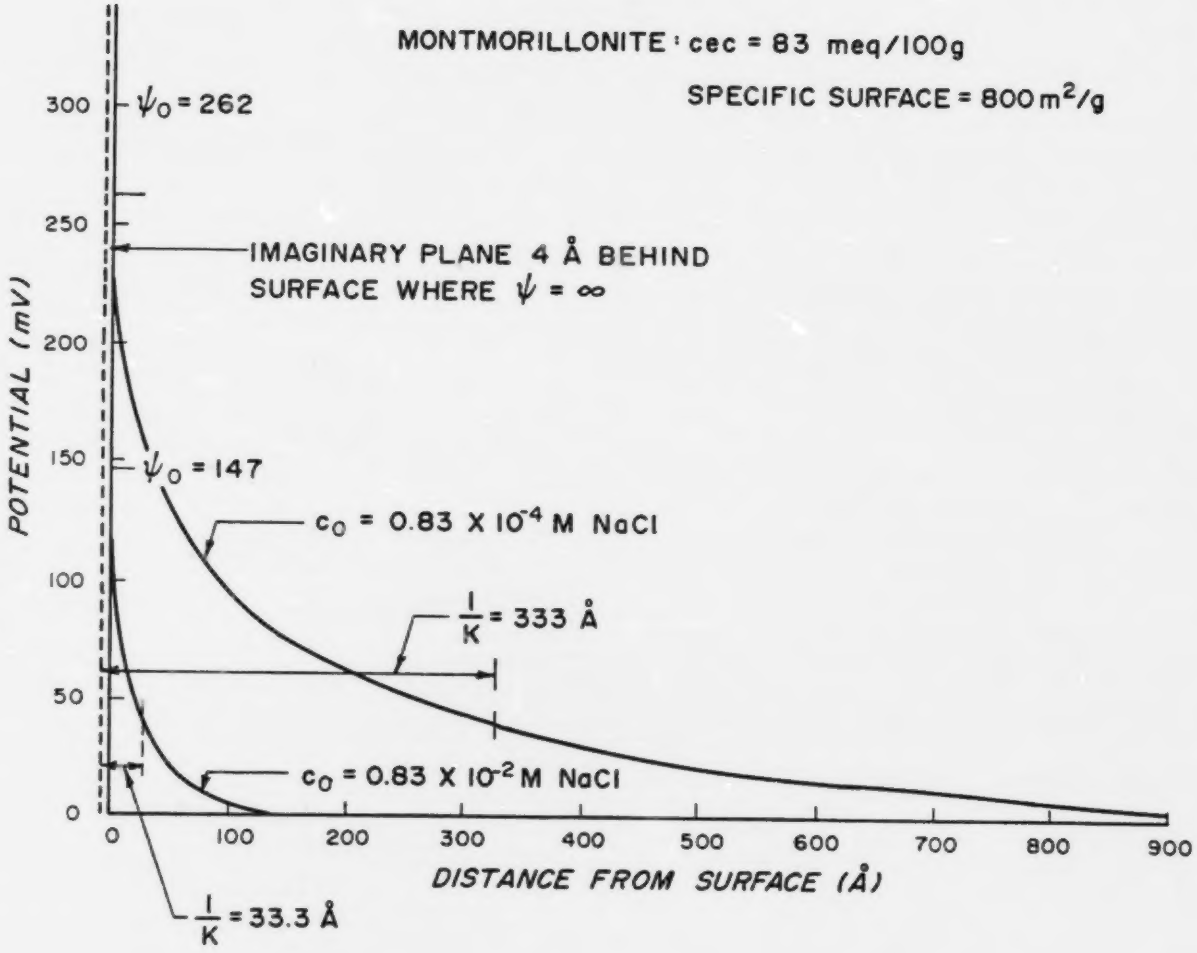

Figure 8. The effect of electrolyte concentration on a double layer potential of montmorillonite clay. (From Hudec, 1979)

the double layer is significantly affected by changes in electrolyte concentration; variations in temperature of the permeant also contribute to changes in the double layer. Hudec conducted permeability tests on 3 cm and 6 cm thick samples and found that when a brine permeant is introduced into a sample of IOL till moulded with fresh water, the permeability is approximately 5 times greater than the same sample permeated with fresh water. The characteristics of the brine used in Hudec's tests are listed in Table 7 and the index properties of the clay till tested are summarized in Table 8. Hudec's tests were conducted on a bulk sample of uncontaminated till from a borrow pit, which was then prepared as three separate samples as follows:

- Sample 1 - fresh water moulding
- Sample 2 - brine moulding water
- Sample 3 - powdered salt and fresh water as moulding solution

The results of Hudec's permeability tests are summarized in Table 9, and indicate that both the duration of the test and the sample thickness had an important influence on the permeability value obtained. He attributes the observed increase in permeability when a fresh water material is subjected to brine to (1) shrinkage of the structure following changes (decreases) in the double layer thickness around clays; (2) a reorientation of clay particles from a dispersed to a flocculated condition; (3) osmotic vapor pressure differences leading to a transfer of fresh water from the clay to brine solution; and (4) hot brine decreasing the double layer thickness and leading to shrinkage of the material. In regard to temperature variations, thermistors installed in the IOL brine pond indicated that brine temperatures could vary from about 3°C to over 40°C as brine solutions are solar heated. The heated brine appears to enhance cracking.

The thin samples used by Hudec in the permeability tests could lead to transverse cracks passing through the entire sample and thus to unrealistic estimates of permeability. Hudec indicates however that the main interpretation of his test data is the relative permeability values rather than actual numerical estimates.

Table 7. Characteristics of brine permeant used in permeability testing of IOL clay till by Hudec.[a]

Brine Permeant	Sample 1	Sample 2	Procor Brine
K (mg/L)	56.17	55.98	20
Na (g/L)	120.32	123.34	135
Ca (mg/L)	970.57	965.26	564
P_2O_5 (mg/L)	2.39	1.73	20
Cl (g/L)	134.77	134.73	220

[a] Source: Hudec (1979).

Table 8. Index tests of clay till from site of the IOL brine pond tested by Hudec.[a]

Parameter	Clay Type	
	Fresh	Salt
Atterberg Limits		
Liquid	29.4	25.1
Plastic	14.4	15.7
Shrinkage	13.9	24.6
Plasticity Index	15.0	9.4
Swelling (Shrinkage) Potential, %	1.6	0.55
Optimum Compaction		
Moisture	12.4	11.3
Density (Dry)	1.99	1.98
Density (Wet)	2.26	2.21
Density, Plastic Limit (remoulded)	2.00	2.01
Permeability (10^{-6} cm/sec)		
3 cm clay thickness		
Fresh water	1.2	ND
Salt water (brine)	5.8	8.6
Recompacted	ND	1.92
6 cm clay thickness		
Fresh water (120 hr)	0.35	ND
Salt water (brine)(240 hr)	0.40	ND

[a] Source: Hudec (1979).

Table 9. Laboratory permeability test results on compacted samples of the IOL brine pond liner.[a]

Moulding Fluid	Sample Height	Permeant	Duration[b] of Test (hr)	Permeability, K x 10^{-6} cm/s Sample No.		
				1[c]	2	3
Fresh	6	fresh	120	0	0.04	1.00
Fresh	6	brine	196	0.11	0.12	0.52
Fresh	3	fresh	24	2.1	0.55	1.1
Fresh	3	brine	24	11.0	0.24	3.1
Fresh	3	brine	+24	12.6	0.28	3.0
Fresh	3	brine	+72	14.2	0.31	2.8
Salt	3	brine	48	0	2.8	7.3
Salt	3	brine	+42	12.4	3.2	7.8
Salt	3	brine	+72	16.3	2.9	6.7
------ sample recompacted -----						
Salt	3	brine	48	1.8	1.1	1.4
Salt	3	brine	+48	3.9	1.2	2.1

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[a] Source: Hudec (1979).

[illegible] A plus sign in front of the hour indicates the continuation of the test under the same conditions.

[c] Sample 1 - fresh moulding
Sample 2 - brine moulding
Sample 3 - fresh water and powdered salt moulding

2.4.3 Chevron Brine Pond, Redwater, Alberta

A surface brine pond in a silty clay and clay material located near Redwater, Alberta was studied by EBA (1971, 1978). At this site, the subsurface materials comprise a relatively homogeneous clay with interbedded silt zones and occasional gravel pockets. An evaluation of the seepage losses from the clay lined pond was conducted in 1978, six years after operation commenced. Samples from the pond sideslopes and pond bottom were obtained by pushing Shelby tubes into the material. The average gradation of several samples was 3% sand, 51% silt, and 46% clay. The average Atterberg Limits for the material studied were: liquid limit of 35%, a plastic limit of 20%, and a plasticity index of 15%. The in-place moisture content averaged about 25% and ranged from 18% to 27%, which is close to the moulding moisture content during sample compaction tests.

Permeability tests were conducted on brine saturated samples obtained from the pond bottom. Distilled water was used as a permeant for all samples. The tests were conducted in a triaxial apparatus with a back pressure to ensure saturation. The results of the permeability tests are summarized in Table 10, and indicate that permeabilities generally range from about 1 x 10^{-8} to 3 x 10^{-9} cm/s. The sample from Test Pit No. 4 had sand/silt layers. It should be noted that consolidation tests conducted in 1971 during the design phase were used to estimate a comparable vertical permeability value of between 5 x 10^{-8} cm/s to 5 x 10^{-9} cm/s.

The clay liners in two adjacent ponds at this site had liner thicknesses ranging from 0.76 m at the top of the liner to 1.5 m in the pond base in one pond, and a minimum thickness of 0.76 m overall in the second pond. Based on a review of the pond performance and construction, it was concluded that a silty zone or silt stratum existed in the retaining structure that allowed relatively high seepage losses.[1] The exposed pond sideslopes and

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[1] It should be noted that a similar situation existed at the Procor brine pond near Redwater.

Table 10. Results of permeability tests on tube samples from Chevron brine pond liner (clayey silt and clay).[a]

Sample Location	Depth (m)	Permeant	Moulding Fluid	Coefficient of Permeability (cm/sec)
500 W (pond floor)	ND	distilled water	("undisturbed") in situ brine	1.27×10^{-8}
Test Pit No. 2	0.9 to 1.2	distilled water	("undisturbed") in situ brine	8.31×10^{-9}
Test Pit No. 2A	0.9 to 1.2	distilled water	("undisturbed") in situ brine	2.96×10^{-9}
Test Pit No. 4	1.2 to 1.5	distilled water	("undisturbed") in situ brine	2.90×10^{-5}

[a] Source: EBA (1978).

pond bottom exhibited alligator cracking and significant shrinkage in response to exposure to the brine. Even though significant cracking near the surface was observed, the materials at depth are generally intact clay and clayey silt materials, which tended to limit seepage. Problems encountered at the Chevron site are related to silty zones through the pond base and dykes allowing concentrated seepage flows.

The Chevron case demonstrates the applicability of clay lined ponds in situations where the effective pond liner thickness (including the compacted zone and the natural materials beneath) tends to limit the seepage losses, even though surface cracking can occur due to the many mechanisms that increase the permeability of clay when exposed to brine.

2.4.4 Dome Brine Pond, Fort Saskatchewan, Alberta

Investigation of the suitability of local clay till for lining a brine pond at the Dome NGL storage facility was conducted by Hardy Associates (1977). Fifteen permeability tests were conducted on samples compacted at various water contents under a constant head of 10 psi. The results of the tests listed in Table 11 show a wide variation in initial moisture contents. Only two of the tests were conducted with a brine permeant (denoted by symbol B in Table 11). In both of these cases, the permeability increased by a factor of between 20 and 63 when compared with permeation with distilled water. The results in Table 11 also illustrate the importance of moulding water content on permeability as discussed previously in Section 2.2.2.

2.4.5 Saskatchewan Till

The effects of brine on the permeability of a typical glacial clay till material from Saskatchewan were tested by the PFRA (1979). The index properties of the materials tested are listed in Table 12. Permeability test results on these materials are summarized for mixtures of fresh water and brine in the moulding liquid and permeant as summarized in Table 13. The tests were performed by

Table 11. Results of compacted permeability tests on clay till from site of Dome NGL brine pond near Fort Saskatchewan.[a]

Test No.	Boring No.	Sample Depth (m)	Dry Density (pcf)	Moulding Water Content (%)	Permeant	Permeability (cm/sec)
1 (B)	45	3.7 to 5.2	114.4	20.3	fresh/	2.25×10^{-8}
					brine	1.43×10^{-6}
2	45	3.7 to 5.2	111.4	20.9	fresh	1.6×10^{-7}
3	45	3.7 to 5.2	114.1	17.4	fresh	1.9×10^{-8}
4	48	3.7 to 4.6	121.9	14.4	fresh	5.2×10^{-9}
5	48	3.7 to 4.6	111.6	19.2	fresh	1.5×10^{-8}
6	49	4.6 to 5.2	111.2	19.9	fresh	4.0×10^{-8}
7	49	4.6 to 5.2	110.1	22.2	fresh	9.0×10^{-9}
8 (B)	50	5.2	115.0	19.2	fresh/	1.6×10^{-7}
					brine	3.4×10^{-6}
9	50	5.2	110.1	18.7	fresh	4.9×10^{-8}
10	51	1.2 to 1.7	108.7	19.9	fresh	5.0×10^{-8}
11	51	1.2 to 1.7	126.9	9.8	fresh	3.2×10^{-9}
12	51	3.7	107.3	19.9	fresh	6.8×10^{-9}
13	51	3.7	109.9	18.7	fresh	7.5×10^{-9}

[a] Source: Hardy (1977).

Table 12. Index tests of Saskatchewan glacial clay till tested by PFRA (1979).

Test No.	Specific Gravity S_s	Atterberg Limits			Grain Size - %		
		Liquid Limit	Plastic Limit	Plastic Index	Sand	0.074 mm	0.002 mm
1	2.734	33	14	19	32	68	24
5	2.754	24	15	9	31	69	26
3	2.734	31	15	16	30	70	27
7	2.747	23	15	8	30	70	27

Table 13. Permeability test results - Saskatchewan clay till.[a]

Test Series	Test No.	Moulding Liquid	Moisture Content (%)	Density (pcf)	Dry Density (pcf)	Permeant	Void Ratio (e)	Permeability	
								k_{20}°C ft/min	k_{20}°C cm/sec
CW	1	Water	Optimum	126.9	107.1	Water	0.592	1.42×10^{-8}	7.21×10^{-9}
CW	5	Water	Optimum	126.3	110.5	Brine	0.557	6.02×10^{-8}	3.06×10^{-8}
CB	3	Brine	Optimum	128.4	107.5	Water	0.586	4.73×10^{-8}	2.40×10^{-8}
CB	7	Brine	Optimum	128.9	111.5	Brine	0.538	7.22×10^{-8}	3.67×10^{-8}

[a] Source: PFRA (1979).

falling head methods on compacted specimens prepared at or near the optimum water content. The gradations of the samples used in these tests are similar to the gradations of the materials collected from the Procor brine pond near Redwater, Alberta. The results of the tests indicate that the introduction of brine results in an increase of permeability of approximately five fold.

2.4.6 Other Reported Laboratory Test Data

Hardcastle and Mitchell (1976) studied the effects of sea water intrusion on the permeability of fresh water sediments. The model they developed investigates the change in pore volume between clusters of particles due to changes in the bound water layer surrounding clay minerals. Permeability tests were conducted on a mixture of crushed basalt and illite clay composed of 57% fine sand, 33% silt, and 10% illite clay. The permeant was 0.6 N salt water solution to model sea water. The tests were conducted by progressively decreasing the electrolyte concentration in the permeant while maintaining a constant gradient of 10. It should be noted that although the tests followed a reverse procedure compared with the tests discussed previously (i.e., introducing brine to a fresh water compacted clay), the results do provide an indication of the effect on behaviour of varying the electrolyte concentration of the permeant.

The laboratory test results indicate that an increase in electrolyte concentration from distilled water to 0.6 N salt solution increases the permeability of the material tested by less than 20%. It should also be noted that the changes in permeability occur relatively rapidly, at less than 0.5 pore volumes[1] of flow through the sample.

McNeal et al. (1966) studied the effect of various salt solutions on the volume-change behaviour of clayey soils. Permeability tests were conducted on two soils having between 13% and 30% clay, of which the dominant clay mineral was montmorillonite

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[1] One pore volume is the volume of permeant required to fill the available pore space in the sample.

(32% and 40% of the clay fraction of each sample, respectively). The results indicate that for a variation in concentration of the permeant from about 800 meq/L to 3 meq/L, approximately one order-of-magnitude change in permeability occurs. These results and other reported data indicate the effect of the solute concentrations on volume changes when montmorillonite constitutes a significant percentage of the clay fraction.

2.5 SUMMARY OF LITERATURE AND CASE RECORDS

A review of the literature on the effect of brine on the interaction with clay minerals leading to changes in permeability indicates that the following factors control behaviour:

- Concentration of the permeant and relative percentage of reactive clay minerals, such as montmorillonite
- The initial arrangement of the aggregate particles as defined by the compaction method or sedimentation method
- The duration of the test; that is, the time required to allow the effect of brine on clay minerals to come to equilibrium
- The size of the sample. For normal testing times (say 2 weeks), only a small portion of the sample becomes saturated with brine
- The method of preparing the sample, saturating the material and conducting the permeability test (i.e., upward or downward permeation through the sample)

A review of case records that illustrate the effect of brine on the permeability of compacted clay soils is summarized in Table 14. These results indicate that a wide variation in permeability values can occur, depending on the variables listed above.

The results of the literature review indicate that, although the factors controlling volume change behaviour and hence permeability changes of compacted clays can be identified, there is currently insufficient laboratory testing data to allow the relative

Table 14. Summary of reported literature on clayey soils - brine interaction and changes in permeability.

Case Record	Sample Type	% Clay Size	Plastic Index	Clay Content % Smectite	 % Kaolinite	 % Illite	Compaction	Permeant	Change in Permeability Due to Brine Introduction
				(% by weight in sample)					
IOL, Redwater (EBA 1978)	from pond liner	21	12	6 to 9	4 to 8	6 to 7	wet of optimum	distilled water	1 order of magnitude
IOL, Redwater (Hudec 1979)	uncontaminated material	ND[a]	ND	ND	ND	ND	ND	brine	increase 5 times
Chevron, Redwater (EBA 1978)	from pond bottom	46	15	ND	ND	ND	at optimum	distilled water	did not test, but lower than IOL
Dome, Ft. Sask. (Hardy 1977)	uncontaminated material	25 to 30	15 to 27	ND	ND	ND	2% wet of optimum	brine and distilled water	increase 20 times to 60 times
Saskatchewan Till (PFRA 1979)	uncontaminated material	32 to 36	10 to 24	ND	ND	ND	at optimum	brine	increase 5 times
Hardcastle and Mitchell (1976)	artificial	10	ND	ND	ND	10	sedimented	0.6 N salt solution	increase 1.2 times
McNeal and Coleman (1966)	natural clays	30	ND	10	ND	ND	sedimented	low conc. salt sol'n.	up to 1 order of magnitude

continued . . .

Table 14. Concluded.

Case Record	Sample Type	% Clay Size	Plastic Index	Clay Content: % Smectite (% by weight in sample)	Clay Content: % Kaolinite (% by weight in sample)	Clay Content: % Illite (% by weight in sample)	Compaction	Permeant	Change in Permeability Due to Brine Introduction
Procor, Redwater (present study)	from pond liner	25	-	4	3	5	2% wet of optimum	hypersaline brine	increase to 1.5 times to 5 times
Procor, Redwater (present study)	uncont. material	25	-	4	2	3	2% wet of optimum	hypersaline brine	up to 1 order of magnitude

[a] ND = No Data Available.

importance of each factor to be determined with great accuracy. It can be stated, however, that for a given compaction method, and moulding moisture content, the most important variable controlling volume change behaviour to brine permeants is the percentage of clay minerals and, more particularly, the percentage of swelling clay such as montmorillonite.

3. LABORATORY TESTING PROGRAM AND RESULTS - REDWATER CLAY TILL LINER

3.1 OUTLINE OF TESTING PROGRAM

Samples of brine-contaminated, compacted clay till and a bulk sample of uncontaminated clay till were collected from the site of a disused brine holding pond owned and operated by Procor Limited near Redwater, Alberta. Details of the site, operation of the pond, and performance are discussed in Section 8.2. A summary of the laboratory test results pertinent to this study are presented in this section. The material investigated is first classified using index tests. The moisture - density relationships for fresh versus brine moulding water content were studied, along with the effects on plasticity of soaking samples with a hypersaline brine solution collected on-site from the adjacent (active) brine pond. Finally, the results of falling head permeability tests on recompacted samples of uncontaminated till and brine-contaminated till, as well as "undisturbed" tube samples, are discussed.

3.2 CLAY TILL MATERIALS

The site of the Procor brine pond is characterized by a relatively homogeneous deposit of stiff to hard clayey silt and sand with some pebbles (clay till). The deposit is about 10 m in thickness and overlies bedrock. Frequent sand stringers and silty zones occur throughout the till unit.

A moisture content profile of natural materials from the project area is presented in Figure 9, indicating that the background moisture contents range from about 8% to 20%, characteristic of compact glacial tills in this region of Alberta. The disused brine pond is understood to have been "lined" with a zone of recompacted and reworked material about 0.5 m to 1.5 m in thickness. A detailed moisture content profile taken from block samples (samples #2, #3, and #4) from the pond bottom is also presented on Figure 9 to illustrate the significant increase in moisture over the natural in situ material. Sample #2 was taken from the upper part

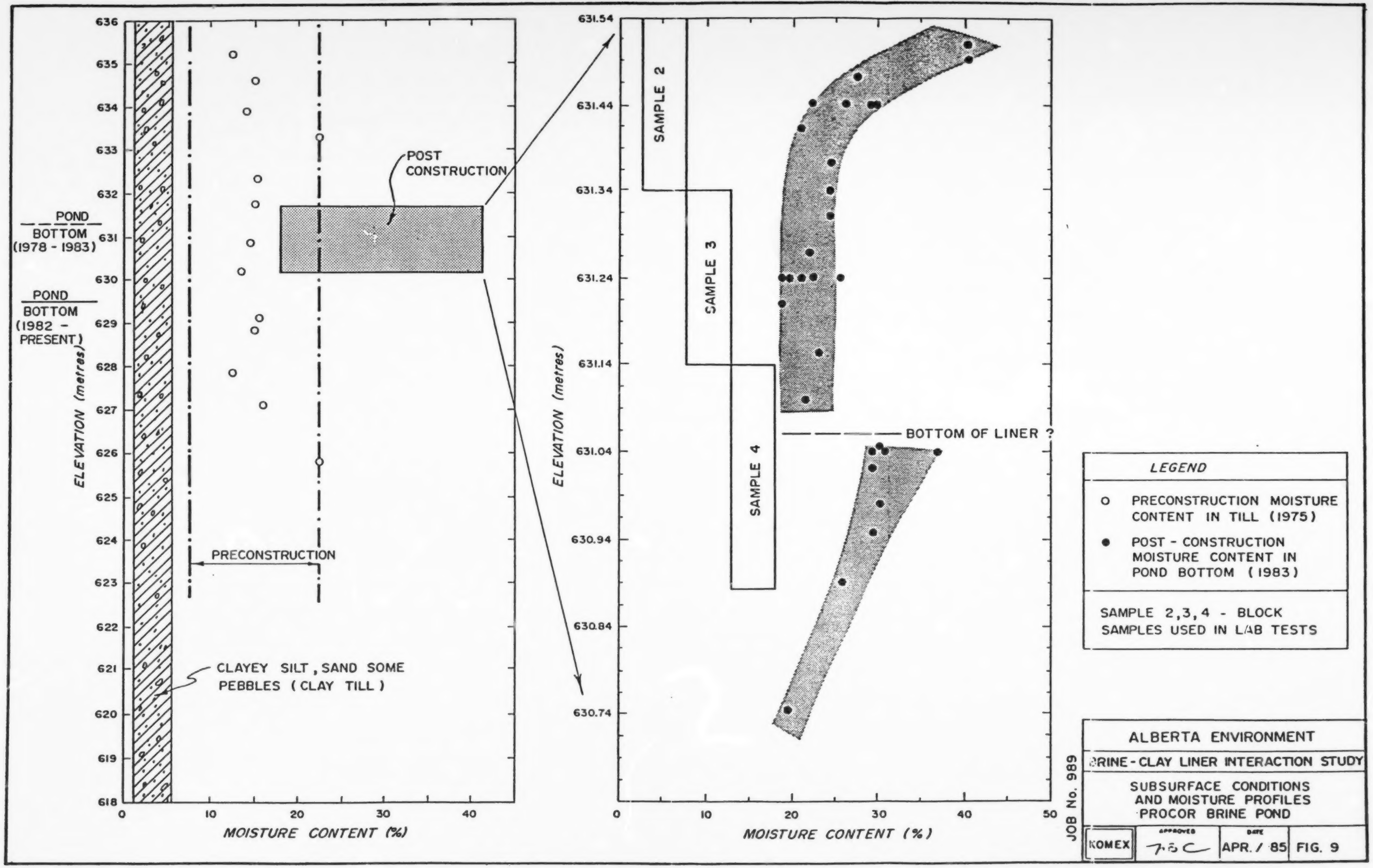


Figure 9. Subsurface conditions and moisture profiles, Procor brine pond.

of the liner (0 - 20 cm), Sample #3 from the middle (20 - 40 cm) and Sample #4 from the bottom (40 - 70 cm). Moisture contents as high as 40% were observed near the pond surface in Sample #1, but became more uniform at about 20% in Sample #3 and the upper part of Sample #4. Moisture content in the middle section of Sample #4 increased to about 30 - 35% before decreasing to 25% at the bottom. The variation in moisture content in Sample #4 could be a reflection of the transition from recompacted liner material to in situ (uncompacted) materials below the liner. Sample #1 is a bulk sample of natural material, and was obtained from a test pit adjacent to the brine pond (refer to Figure 36 in Section 8.2 for location).

The gradational characteristics of the four samples are summarized in Figure 10. As indicated, the materials are very similar, with a clay content (i.e., % finer than 0.002 mm) ranging from about 20% to 27% by weight. Plasticity characteristics of the fine fraction were conducted for each sample and are summarized in Figure 11. The results for the Atterberg limits, conducted using distilled water (ASTM D423, D424), indicate that the material is a clay with low plasticity; the plotting of Sample #4 shows that it is a silt of low plasticity (ML). The effect of brine on plasticity is discussed below.

Scanning electron microscope (SEM) and X-ray diffraction analyses were conducted on Sample #1 (uncontaminated till) and Sample #2 (brine-contaminated till from a block sample near the surface of liner). The results of these analyses are presented in Section 8.4 and can be summarized as follows:

1. Clay minerals form 9% of the bulk composition of Sample #1 and 13% of the bulk composition of Sample #2.
2. The glycolated clay fraction analysis for the two samples is as follows:

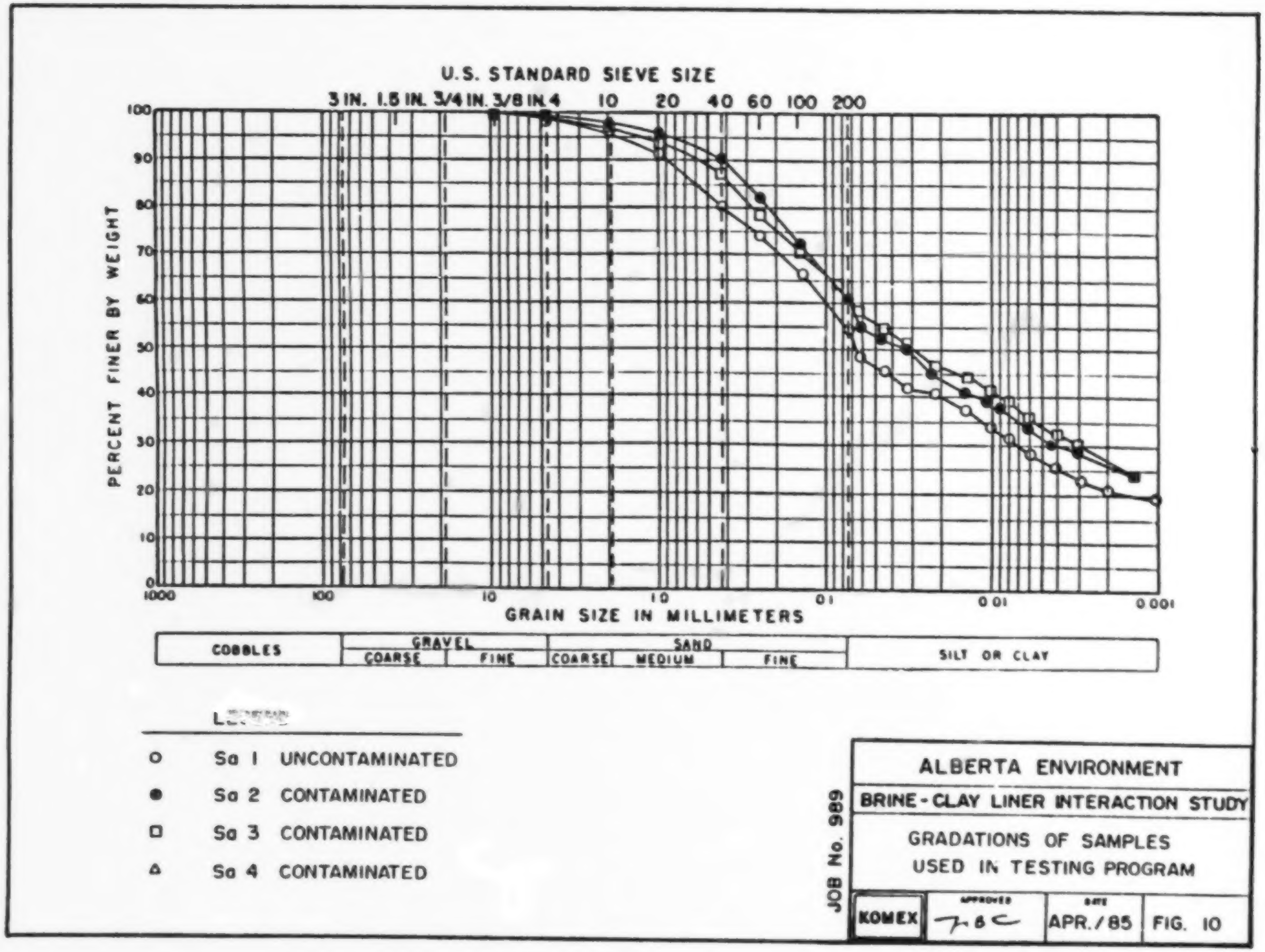
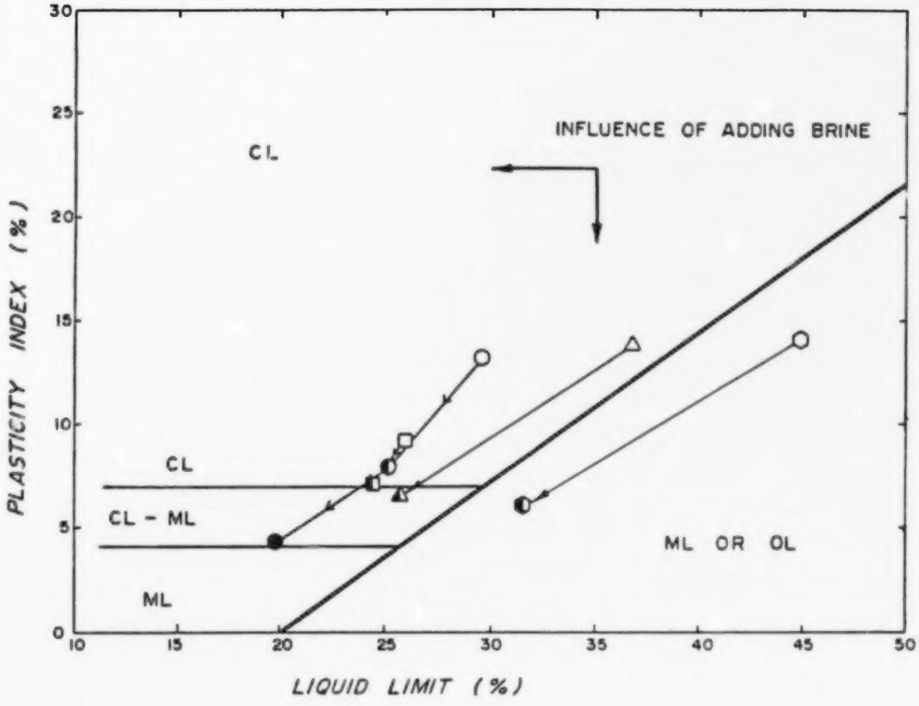


Figure 10. Gradations of samples used in testing program.



LEGEND				
SAMPLE No.	TYPE	DISTILLED H_2O	BRINE (NO SOAKING)	BRINE SOAK (96 hrs)
1	UNCONTAMINATED	○	◐	● (96 HRS)
2	CONTAMINATED	△	▲	
3	CONTAMINATED	□	◧	
4	CONTAMINATED	○	◑	

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FIG. 11

Figure 11. Effect of brine on plasticity.

PERCENTAGE OF CLAY MINERALS IN CLAY SIZED FRACTION

SAMPLE	KAOLINITE	ILLITE	CHLORITE	SMECTITE (montmorillonite)
1	20%	31%	7%	42%
2	23%	36%	9%	32%

3. The clays are mainly detrital and coat larger grains of the sample (refer to SEM photographs in Section 8.4).
4. Smectite clay in samples #1 and #2 is largely calcium-rich, and has a lower propensity to swell than the sodium-rich type. The brine saturation of Sample #2 does not appear to have affected the cation type.
5. Sodium chloride crystals have precipitated from the brine as thin films or fine irregularly shaped crystals in Sample #2. The exposure to brine appears to have had only a minor influence on the characteristics of the clays or the structure of the aggregate.

The majority of the falling head permeability tests were conducted on Sample #1 (uncontaminated till) and Sample #2 (highly brine-contaminated till). The moisture - density relationship (Standard Proctor) for samples #1 and #2 using tap water versus brine as a moulding fluid are summarized in Figure 12. The effect of brine moulding fluid on compaction characteristics is discussed in the following section.

3.3 CHEMICAL CHARACTERISTICS OF SOILS AND PERMEANTS

Chemical analyses were conducted on the four soil samples and the brine permeant. The results of the analyses are presented in Section 8.5. The soil samples were saturated with distilled water to form a paste, and chemical analyses were conducted on the filtered extract. The results of the analysis on the four soil

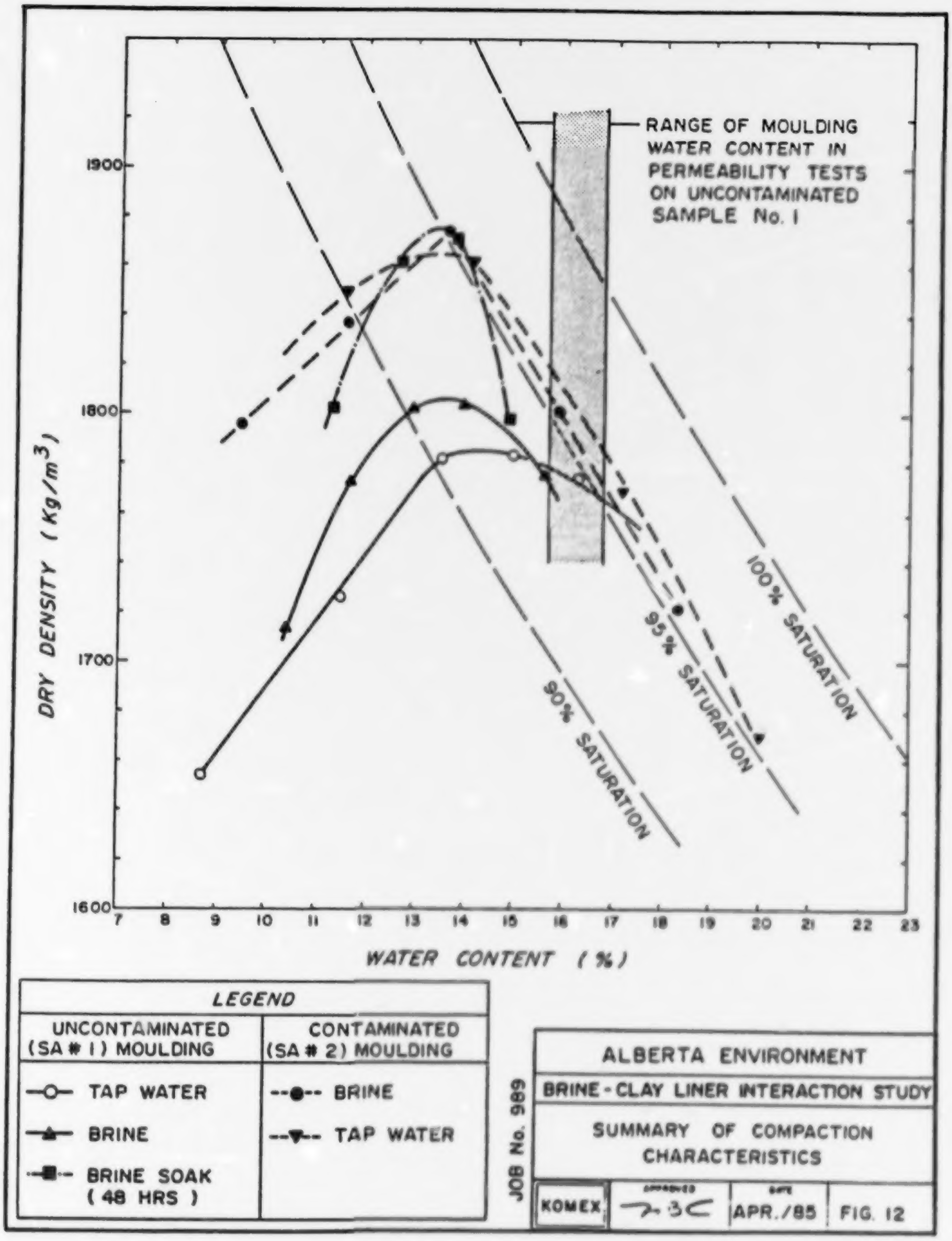


Figure 12. Summary of compaction characteristics.

samples is considered to be representative of the pore water chemistry as sampled in the field. The results of this analysis are summarized in Table 15. The marked influence of brine contamination is evident, although the variation in brine content (NaCl) with elevation in the liner was unexpected. The higher concentration in Sample #4 compared with Sample #2 could be a reflection of surface cracking and infiltration with fresh water, resulting in a diluted concentration in the near surface zone. It should be noted that a check analysis was conducted on Sample #4, which confirmed the trend noted in Table 15.

The chemical characteristics of the permeants used in the falling head permeability tests and for sample preparation are listed in Table 16. A bulk sample of brine was collected from an operating pond at the Procor site. The "fresh water" permeant is Calgary tap water; the chemical analysis of Calgary tap water was provided by the City of Calgary. It should be noted that the brine is a hypersaline solution with a specific gravity of 1.36 and a total dissolved solids of 356 g/L. This brine solution is much more concentrated than most salt water solutions considered in the literature (compare sea water at 0.6 N to Procor brine at 355 N).

3.4 EFFECTS OF BRINE ON PLASTICITY

The effect of adding brine to an air-dried sample of clay till from the Procor site is illustrated in the plasticity chart in Figure 11. As indicated, the brine tends to reduce both the liquid limit and plasticity index, changing the classification from a clay of low plasticity to a silt of low plasticity. This change could be a reflection of the influence of highly concentrated salt solution on the bound water layer surrounding clay minerals, which controls plasticity. The effect of the duration of brine soaking on plasticity was evaluated by conducting tests for Atterberg limits at various times of soaking. The results of this study are summarized in Figure 13, and indicate that after about two days of soaking, very little change in plasticity and liquid limit occurs. The effect of a four-day soaking period on plasticity characteristics is also

Table 15. Chemistry of pore water in samples of clay till materials from Procor brine pond site.

Sample (mg/L)	#1 Uncontaminated Clay Till	#2 Contaminated Clay Till	#3 Contaminated Clay Till	#4 Contaminated Clay Till
Chloride	40.6	38 000	53 000	79 000 (61 000)[a]
pH	6.95	ND	7.91	ND
Bicarbonate	121	ND	122	ND
Sulphate	30.5	ND	225	ND
Sodium	16.2	25 200	34 800	52 000 (39 100)[a]
Potassium	1.12	8.50	10.1	11.9
Calcium	36.7	72.0	116.0	223.0
Magnesium	17.4	11.5	17.5	29.0

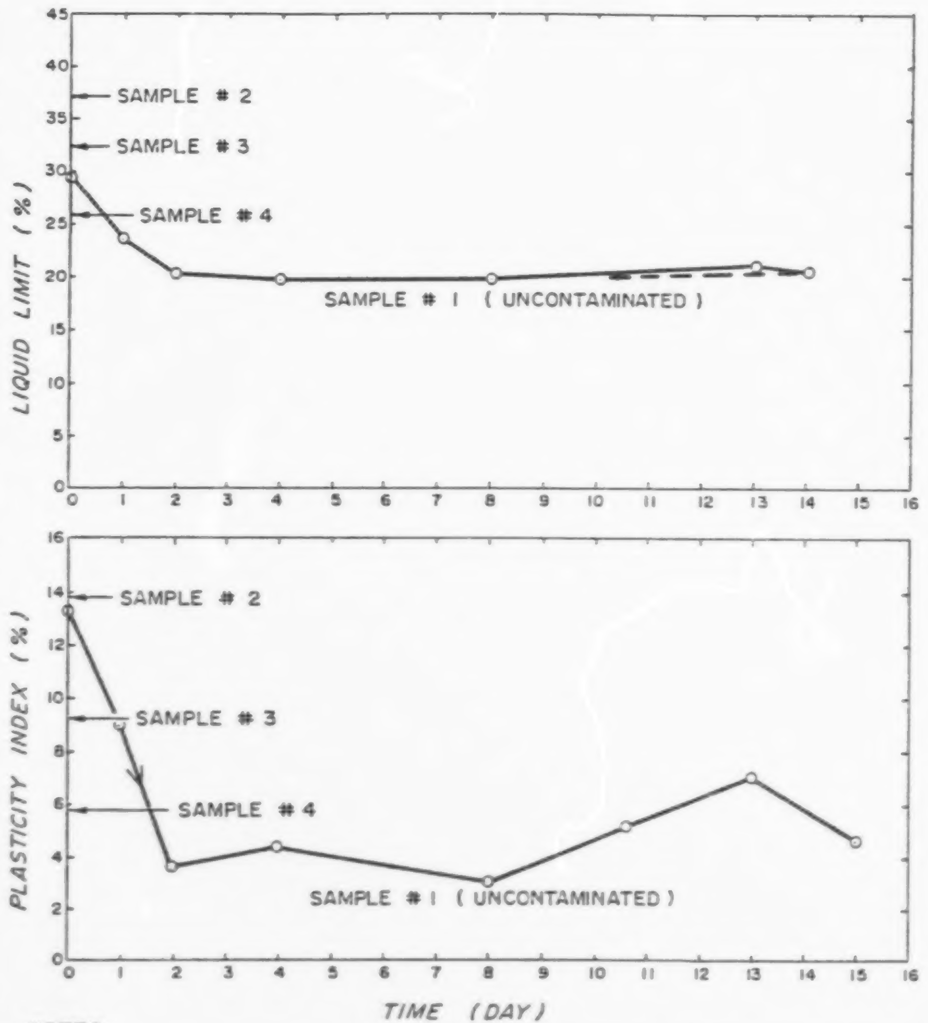
[a] Analysis checked to confirm unexpected variation in brine content.

Table 16. Chemical characteristics of permeants used in hydraulic conductivity tests of Redwater clay till.

		Brine[a]	Tap Water[b]
pH		6.95	8.15
conductance (μmhos/cm)	exceeds	200 000	300
chloride (mg/L)		220 000	3
bicarbonate (mg/L)		121	175
sulphate (mg/L)		1 150	60
sodium (mg/L)		135 000	3
potassium (mg/L)		20.5	0.75
calcium (mg/L)		564	60
magnesium (mg/L)		43.2	15
total dissolved solids (TDS) (mg/L)		356 838	220
specific gravity (g/cm^3)		1.36	1.00
sodium adsorption ratio (SAR)		1 473	0.09
NaCl concentration (meq/L)		355 000	6
(N)		355	0.006

[a] Sample taken from active brine pond near Redwater, Alberta (Procor site), September 1984.

[b] Typical City of Calgary test data for 1983.



NOTES:

1. SAMPLES 2,3 AND 4 ARE BRINE CONTAMINATED FROM THE POND BOTTOM (INSITU SAMPLES)
2. THE SALT CONTENT INCREASES FROM SAMPLES 2 TO 4.

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ALBERTA ENVIRONMENT

BRINE - CLAY LINER INTERACTION STUDY

EFFECT OF BRINE SOAKING
ON PLASTICITY OF
UNCONTAMINATED SAMPLE # 1

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Figure 13. Effect of brine soaking on plasticity of uncontaminated Sample #1.

indicated on the plasticity chart in Figure 11, indicating a further reduction in liquid limit. The results of these tests indicate that the maximum influence of brine on plasticity characteristics of the clay till considered in this study occurs after about 48 hours of soaking with a hypersaline brine solution. Thus, in the permeability testing program, where pretreating an uncontaminated sample with brine was studied, samples were soaked for at least 48 hours.

The plasticity changes shown in Figure 13 indicate that soaking in a concentrated brine solution (Table 16) reduces the plasticity index to the range of the in situ values for Sample #4 (highest salt content). The data also suggest that the plasticity of the uncontaminated sample is similar to that of Sample #2 from the pond bottom, which in turn suggests that the brine-saturated liner is diluted with fresh water, as the changes are reversible. This observation may substantiate the observed trend of the chemical analyses listed in Table 15. The plasticity changes indicated in Figure 13 also suggest that the "brine-soaked" samples of initially uncontaminated clay till (Sample #1) may represent a worst case condition in which the maximum possible effect of brine on clay minerals is allowed to occur prior to permeability testing.

3.5 DISPERSION CHARACTERISTICS OF PROCOR CLAY TILL

The dispersion characteristics were estimated by the double hydrometer test as discussed by Sherard et al. (1976).

By this method, the ratio of the percentage finer than two microns for hydrometer tests run with and without dispersant is defined as a qualitative measure of the dispersion potential of a material. The results of these tests shown in Figure 14 indicate that the uncontaminated material (Sample #1) exhibits no dispersion, whereas the contaminated Sample #2 exhibits about 100% dispersion. One hundred per cent dispersion indicates a very high propensity to disperse when fresh water is added to a brine-saturated material, which is a situation that can occur on the exposed sideslopes of an operating brine pond.

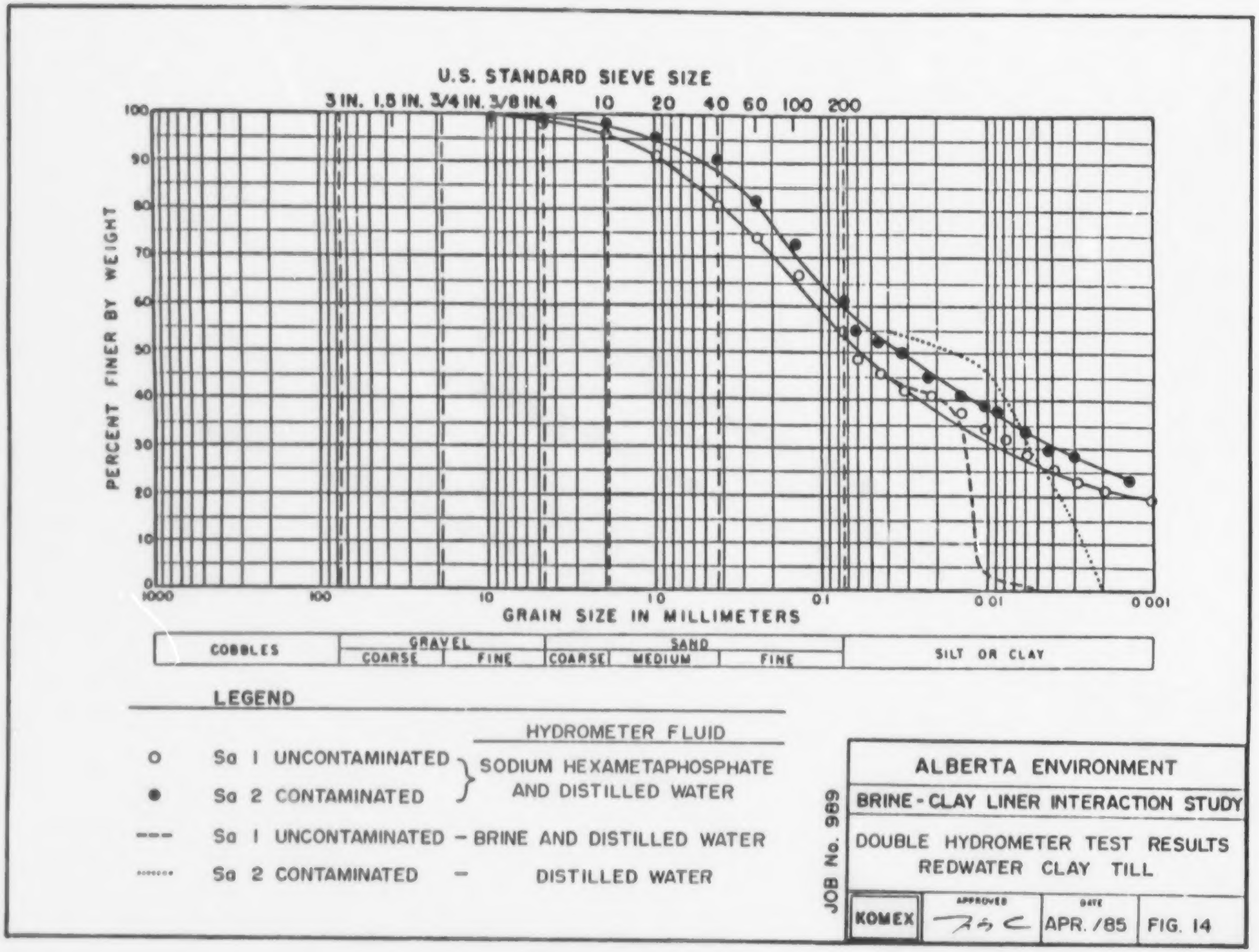


Figure 14. Double hydrometer test results, Redwater clay till.

The possibility of particle dispersion and loss of particles from the aggregate structure as water seeps through the mass is particularly important in the near-surface zone of the brine pond. In this zone, surface cracking could occur and, during the operation of the pond, fresh water from make-up or precipitation could enter the cracks, leading to clay particle dispersion, erosion of material, and possibly a piping failure to an underdrain.

3.6 EFFECT OF BRINE ON LINER PERMEABILITY

The permeability testing program is described in Section 8.3. Falling head tests were conducted on three types of samples as follows:

- Type 1 - Compacted, uncontaminated clay till
- Type 2 - Compacted, brine-contaminated clay till from block samples collected in pond bottom
- Type 3 - "Undisturbed" tube samples cut from block samples obtained from pond bottom

In addition, an oedometer test (Type 4) was conducted on an "undisturbed" sample cut from block Sample #2. The permeability was then calculated from the time-compression characteristics using one-dimensional (Terzaghi) consolidation theory.

The results of the testing program are summarized in Table 17. The compaction characteristics and moisture changes during testing (i.e., saturation) are important variables that affect laboratory test results. These factors are summarized in Figure 15. The influence on permeability of these factors is separated from the effect of brine, which is the main area of investigation in this study. The specific results for each test are also discussed briefly in the following section.

3.6.1 Type 1 - Compacted, Uncontaminated Clay Till

A total of five falling head tests were conducted on Sample #1 (uncontaminated clay till). All samples were compacted to

Table 17. Summary of permeability tests on Procor clay till liner.

Test No.	Sample Type	Moulding	Permeant	Initial % Saturation	Final % Saturation	Change in Moisture (%)	% -2 Micron (% Clay Mineral Content)	Plastic Index	Permeability (cm/sec x 10^{-8}) Initial Stabilized	Change in Permeant	Effect of Change in Permeant
1	1	F	F - B	95	95	+0.4	25 (9)	13.0	2.0	to brine	increase to 20.0
2	1	B	B	94	96	+1.1	30 (9)	8.0	1.5	-	-
3	1	B	F	94	101	+4.0	23 (9)	8.1	1.0	-	-
4	1	B (soaked)	F - B	93	100	+4.7	28 (9)	3.6	1.5	to brine	increase to 1.75
5	1	B (soaked)	B	91	92	+0.3	29 (9)	3.6	0.25	-	-
6	2	F	F - B	96	99	+1.8	29 (13)	13.9	0.4	to brine	increase to 0.6
7	2	B	B	95	94	-0.8	36 (13)	6.9	0.5 (reducing to 0.15)	-	-
8	3	B	B	96	105	+8.0	32 (-)	7.1	0.8	-	-
9	2	"undisturbed"	B	-	-	-	26 (13)	7.0	18.0	-	-
10	3	"	B	-	-	-	26 (-)	7.0	15.0	-	-
11	2	"	brine in cell	-	-	-	26 (13)	-	10.0	-	-

Notes: F = fresh water (tap water), B = brine solution from Redwater pond.

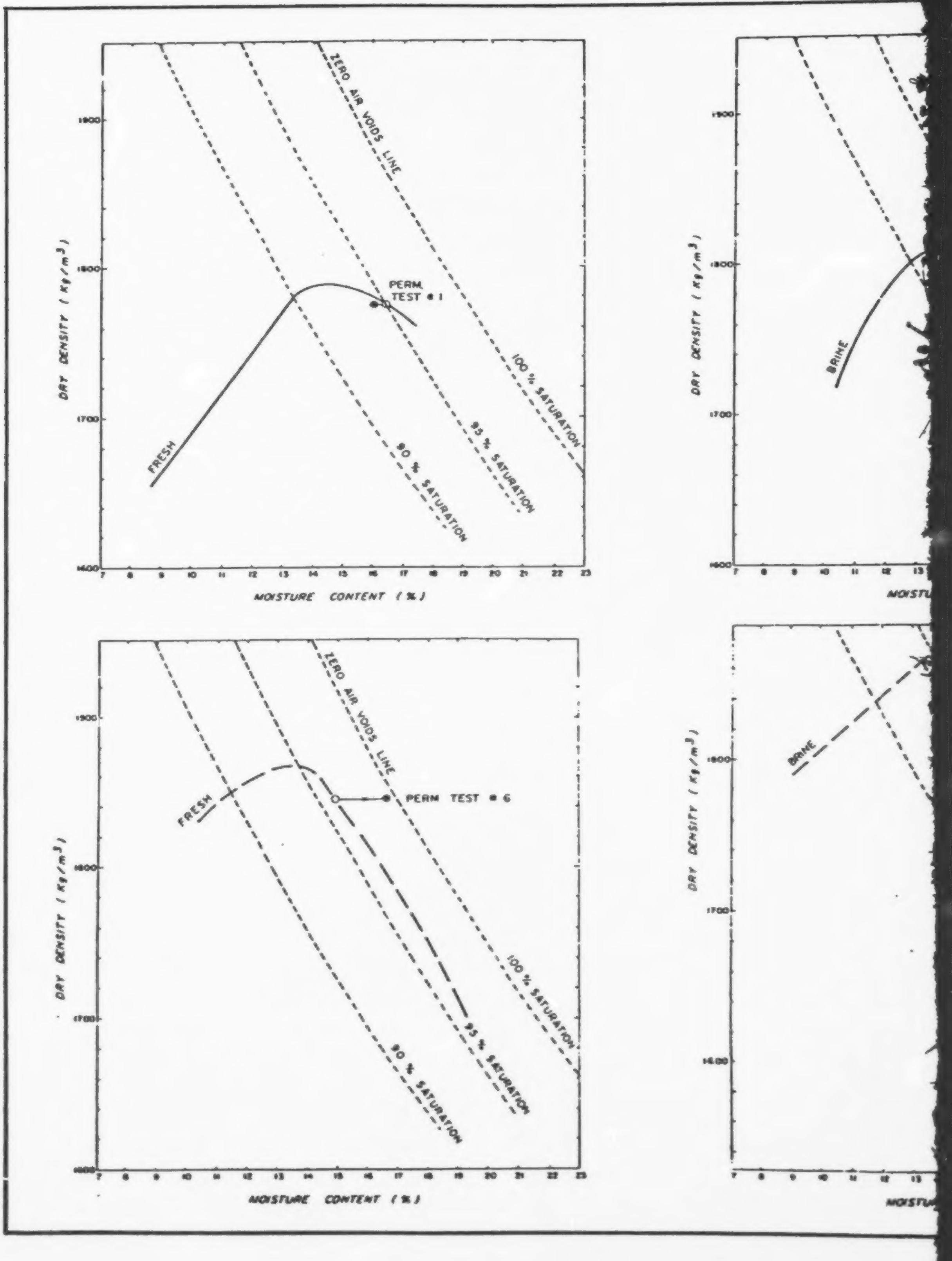
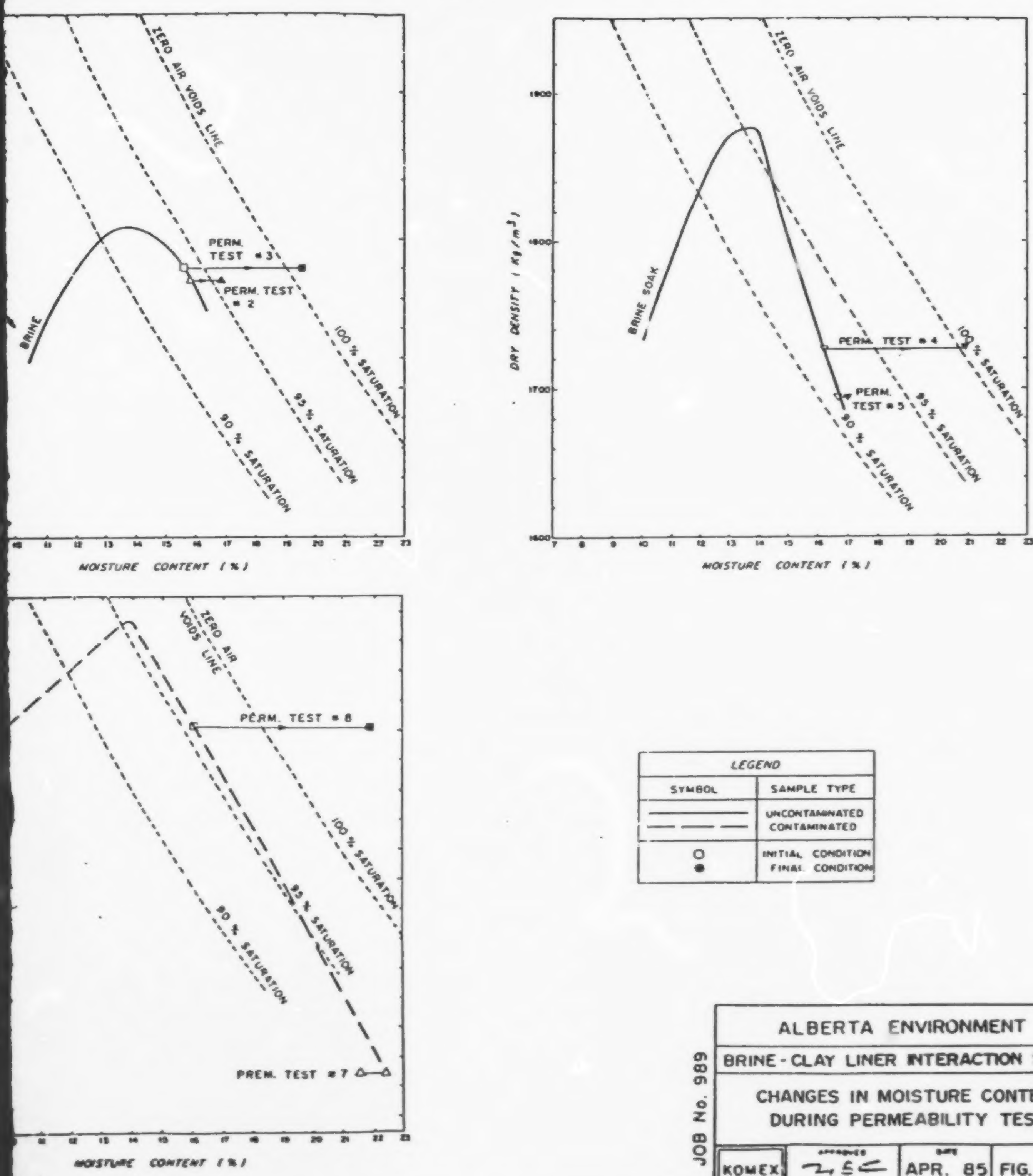


Figure 15. Changes in moisture content during permeability tests



JOB No. 989

ALBERTA ENVIRONMENT

BRINE - CLAY LINER INTERACTION STUDY

CHANGES IN MOISTURE CONTENT DURING PERMEABILITY TESTS

KOMEX	APPROVED 2, E C	DATE APR. 85	FIG. 15

y tests.

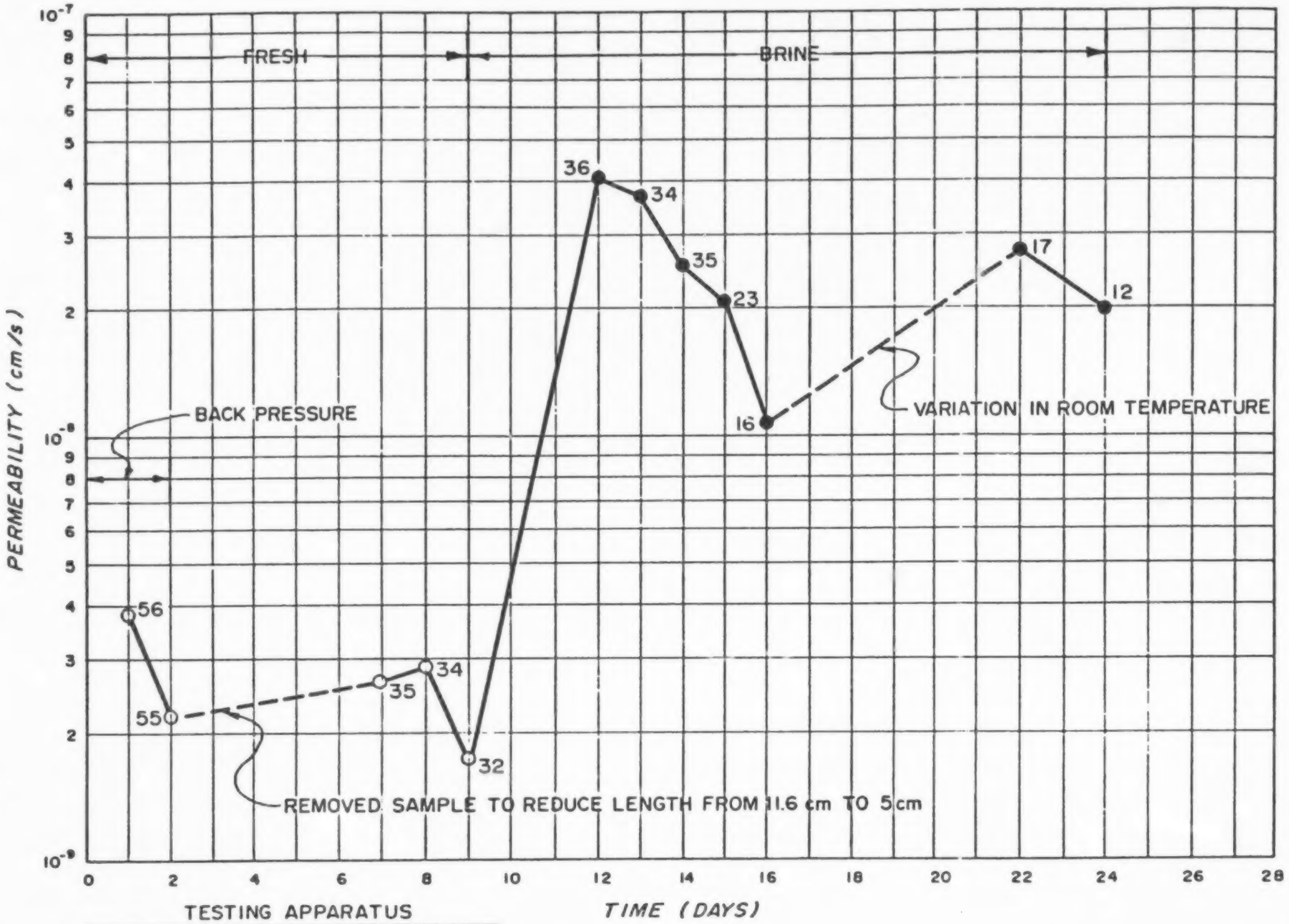
about 90% to 95% of the maximum dry density as determined by the Standard Proctor Test (ASTM D698). The moisture content was selected as at least 2% wet-of-optimum to provide a more workable material, to limit the variability in permeability with moulding moisture content and to aid in saturation. The initial moisture contents and changes during the permeability tests are summarized in Figure 15. This figure illustrates the saturation changes during each test and also indicates that several tests were actually conducted on partially saturated samples. The implications of this condition are discussed below.

Test #1: Fresh/Fresh-Brine: Test #1 (Figure 16) was prepared using tap water as a moulding fluid and brine was introduced as a permeant. When brine was introduced, the permeability increased by about one order of magnitude over a three-day period, then fluctuated and levelled off to about 2×10^{-8} cm/s. The hydraulic gradient on the sample changed considerably during the test, but it was found that variations in the hydraulic gradient caused only small variations in the test results.

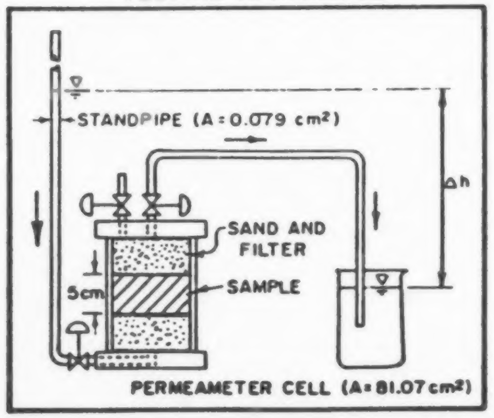
Test #1 is an important test result because it represents a common situation where a brine pond might be planned and samples of native materials in the area collected for permeability testing in the laboratory. The introduction of brine to the uncontaminated material with fresh water moulding appears to have an appreciable influence on permeability. Although the sample saturation was relatively low during the test (i.e., 95% saturated) and the measured values of permeability were likely lower than saturated values, the relative values before and after introduction of brine is an important observation.

Test #2: Brine/Brine: Test #2 represents the situation in the field where brine is added to a native soil as a moulding fluid and immediately compacted. No "soaking period" is modelled by this test.

In Test #2 (Figure 17), brine was used as both the moulding fluid and the permeant. The large variation in permeability after day 4 of the test has been attributed to probable



TESTING APPARATUS



LEGEND

O^{34} AVERAGE STABILIZED VALUE FOR DAY, GRADIENT = 34

TEST No. I

SAMPLE No.: I

SAMPLE TYPE: UNCONT.

MOULDING LIQUID: FRESH

PERMEANT: FRESH/BRINE

INITIAL MATERIAL PROPERTIES

	% Passing 75μ	% Passing 2μ	W_L	W_P	P.I.
CLASSIFICATION	56	25	29.7	16.5	13.2

	% Clay Minerals	Clay Components
SEM	9	SMECTITE : 32 % ILLITE : 36 % KAOLINITE : 23 %

COMPONENT	[Cl⁻] mg/L	[Na⁺] mg/L	SAR
INITIAL PORE FLUID CHEMISTRY	40.6	16.2	0.55
BRINE PERMEANT	220,000	135,000	1473
FRESH WATER PERMEANT	3	3	0.09

COMPACTION PROPERTIES

	Moisture Content, w(%)	Dry Density, γ_D,(kg/m^3)
STANDARD PROCTOR	14.2	1788
START OF TEST	16.5	1754
END OF TEST	16.1	1779

JOB No. 989

ALBERTA ENVIRONMENT

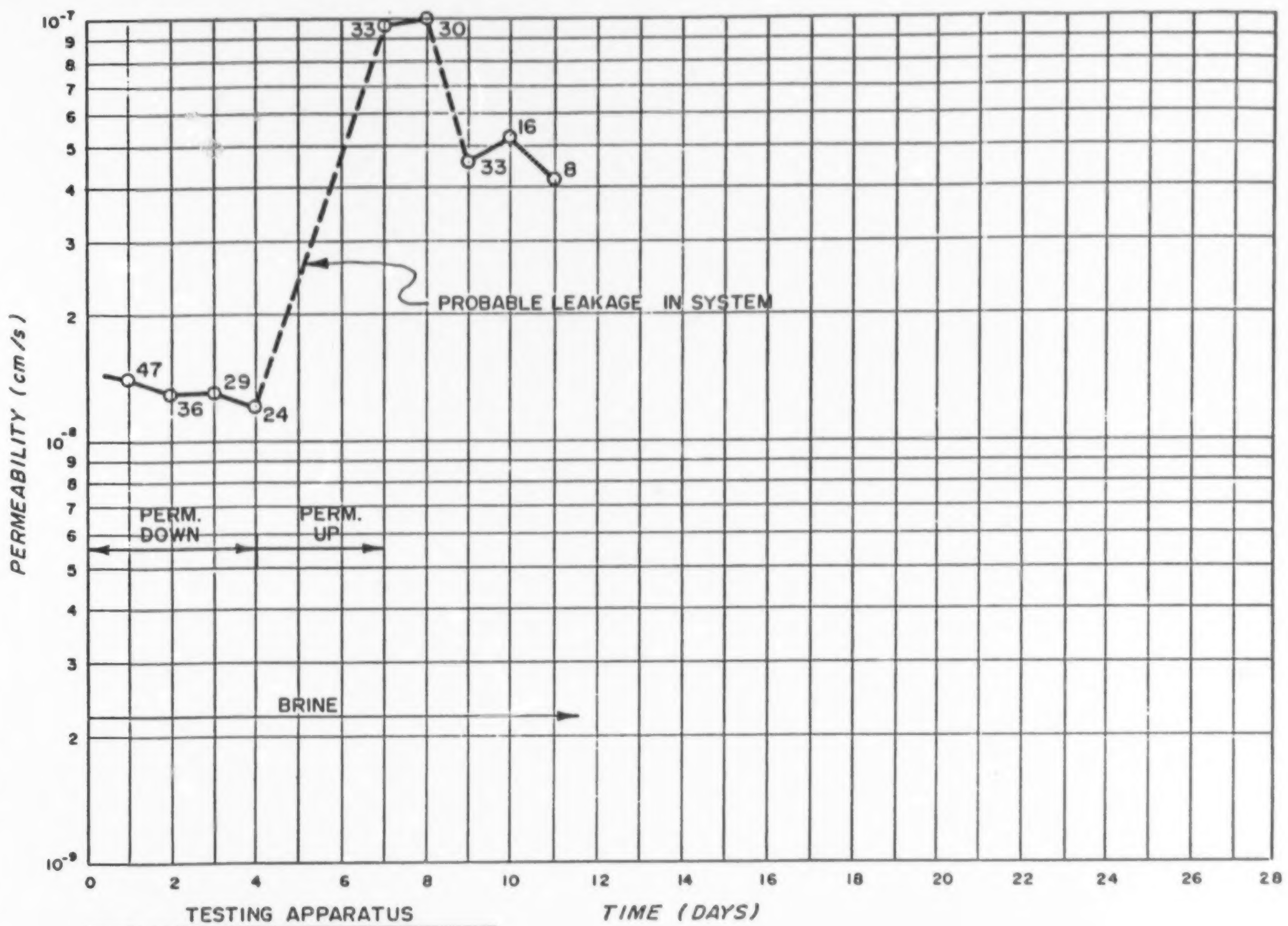
BRINE - CLAY LINER INTERACTION STUDY

FALLING HEAD PERMEABILITY

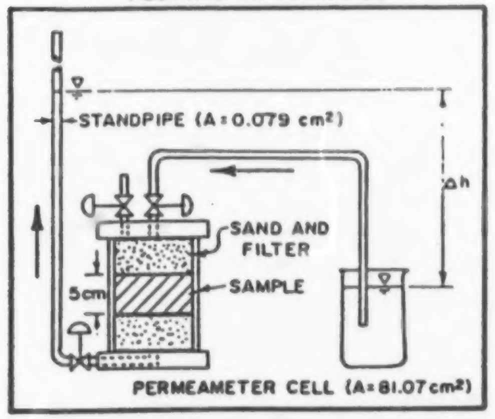
TEST No. I

KOMEX	APPROVED	DATE	
	7.SC	APR. /85	FIG. 16

Figure 16. Falling head permeability, Test No. 1.



TESTING APPARATUS



LEGEND

o^{34} AVERAGE STABILIZED VALUE FOR DAY, GRADIENT = 34

TEST No. 2

SAMPLE No.: 1 SAMPLE TYPE: UNCONT.

MOULDING LIQUID: BRINE PERMEANT: BRINE

INITIAL MATERIAL PROPERTIES

	% Passing 75μ	% Passing 2μ	W_L	W_P	P.I.
CLASSIFICATION	59	30	25.1	17.0	8.1

	% Clay Minerals	Clay Components
SEM	9	SMECTITE : 32 % ILLITE : 36 % KAOLINITE : 23 %

COMPONENT	[Cl⁻] mg/L	[Na⁺] mg/L	SAR
INITIAL PORE FLUID CHEMISTRY	← BRINE MOULDING →		
BRINE PERMEANT AND MOULDING	220,000	135,000	1473

COMPACTION PROPERTIES

	Moisture Content, w(%)	Dry Density, γ_D, (kg/m³)
STANDARD PROCTOR	13.6	1810
START OF TEST	15.8	—
END OF TEST	16.9	—

JOB No. 686

ALBERTA ENVIRONMENT
BRINE-CLAY LINER INTERACTION STUDY
FALLING HEAD PERMEABILITY
TEST No. 2

KOMEX	APPROVED 7BC	DATE APR. /85	FIG. 17

Figure 17. Falling head permeability, Test No. 2.

leakage in the system, as well as a reversal in permeation direction. It should be noted that unless otherwise stated, all of the tests were conducted by permeating upward through the sample to aid in saturation and the release of trapped air bubbles in the system. Additionally, it should be noted that the largest variations in permeability of the samples are for tests #1 and #2, both of which appeared to be at about 95% saturation level at the end of the test. Thus, these fluctuations in permeability could be in part due to the partially saturated state of the samples.

Test #3: Brine/Fresh: Test #3 was conducted on initially uncontaminated material with brine as a moulding liquid and fresh water as a permeant. This test represents a case in which natural materials are "treated" by adding brine, then fresh water from snowmelt or make-up water is impounded and permeates the material.

The results of this test, shown in Figure 18, indicate a very stable and relatively constant permeability. The material was essentially 100% saturated at the end of the test and it is noted in Table 17 that the material increased in moisture content by 4%, indicating swelling of the clay minerals. Although the test was conducted for only 12 days, the trend of permeability is to decrease with time, which is consistent with the swelling of clay minerals and the increase in moisture content.

Test #4: Brine Soak/Fresh-Brine: In Test #4, Sample #1 was soaked with brine for 48 hours then permeated with fresh water followed later by a brine permeant. The results of the test are shown in Figure 19 and indicate that the permeability is relatively constant with time, although an increasing trend is noted. In this test, the material becomes essentially 100% saturated at the end of the test and the moisture content of the sample increases by about 5%, as indicated in Table 17. The effect of changing the permeant from fresh water to brine does not appear to have any appreciable influence on permeability.

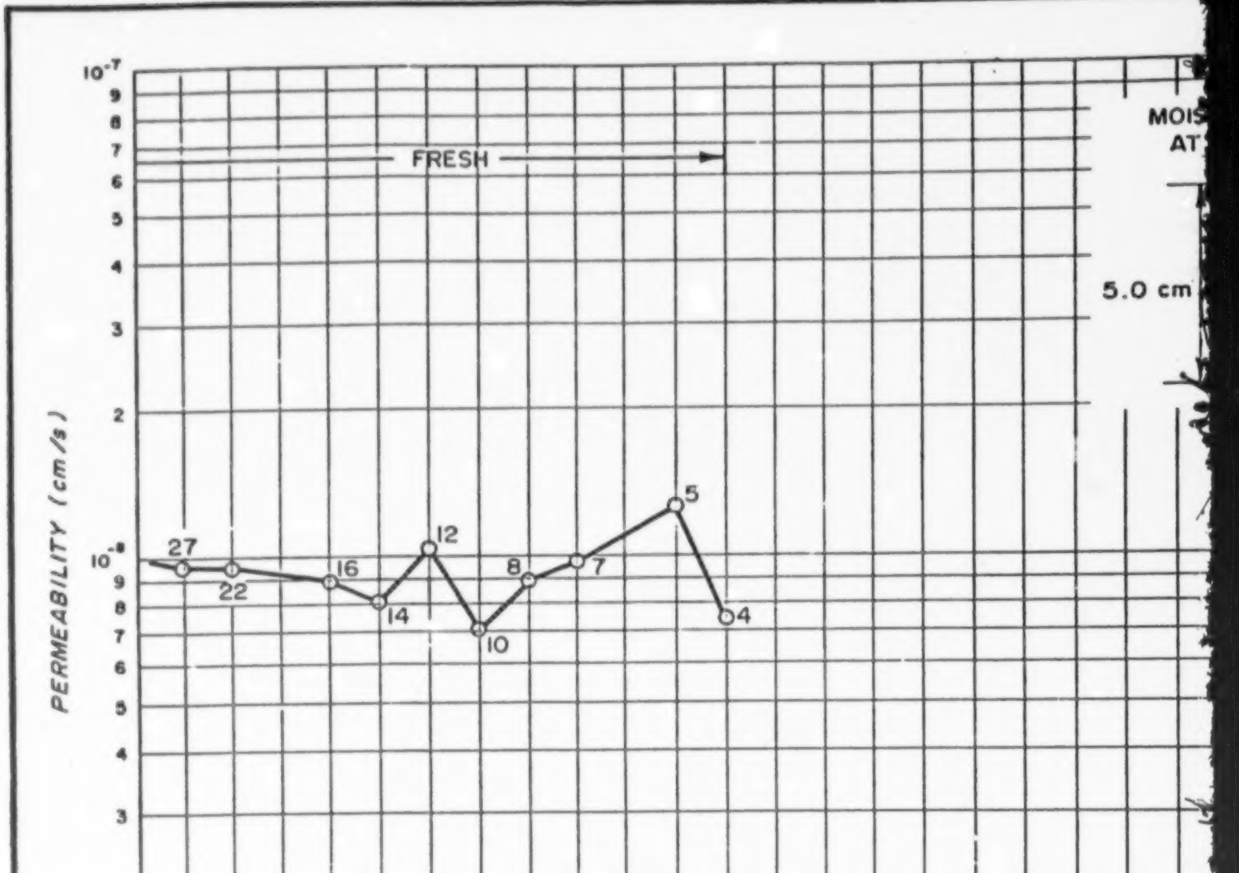
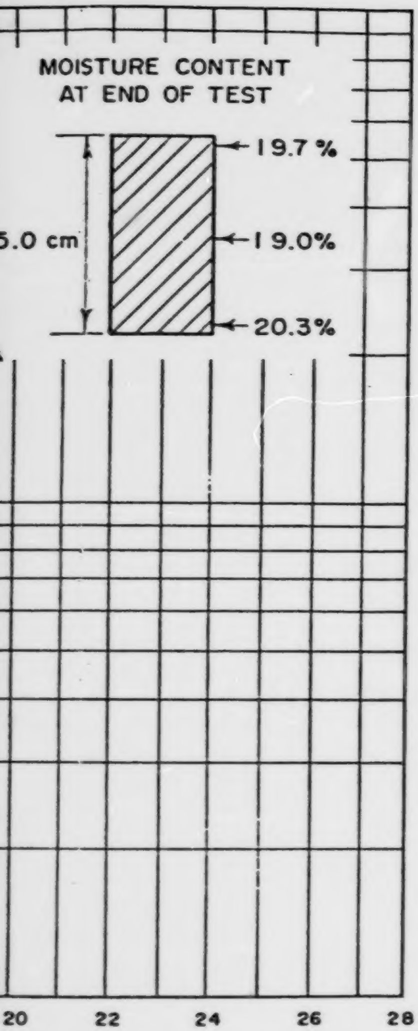


Figure 18. Falling head permeability, Test No. 3.



ED VALUE
T = 34

TEST No. 3

SAMPLE No.: 1	SAMPLE TYPE: UNCONT.
MOULDING LIQUID: BRINE	PERMEANT: FRESH

INITIAL MATERIAL PROPERTIES

	% Passing 75μ	% Passing 2μ	W_L	W_P	P.I.
CLASSIFICATION	54	23	25.1	17.0	8.1

	% Clay Minerals	Clay Components
SEM	9	SMECTITE : 32 % ILLITE : 36 % KAOLINITE : 23 %

COMPONENT	[Cl⁻] mg/L	[Na⁺] mg/L	SAR
INITIAL PORE FLUID CHEMISTRY	←— BRINE MOULDING —→		
BRINE MOULDING	220,000	135,000	1473
FRESH WATER PERMEANT	3	3	0.09

COMPACTION PROPERTIES

	Moisture Content, w(%)	Dry Density, γ_D, (kg/m^3)
STANDARD PROCTOR	13.6	1810
START OF TEST	15.6	—
END OF TEST (AVER.)	19.6	—

JOB No. 989

ALBERTA ENVIRONMENT

BRINE-CLAY LINER INTERACTION STUDY

FALLING HEAD PERMBILITY
TEST No. 3

KOMEX	APPROVED 7BC	DATE APR. /85	FIG. 18

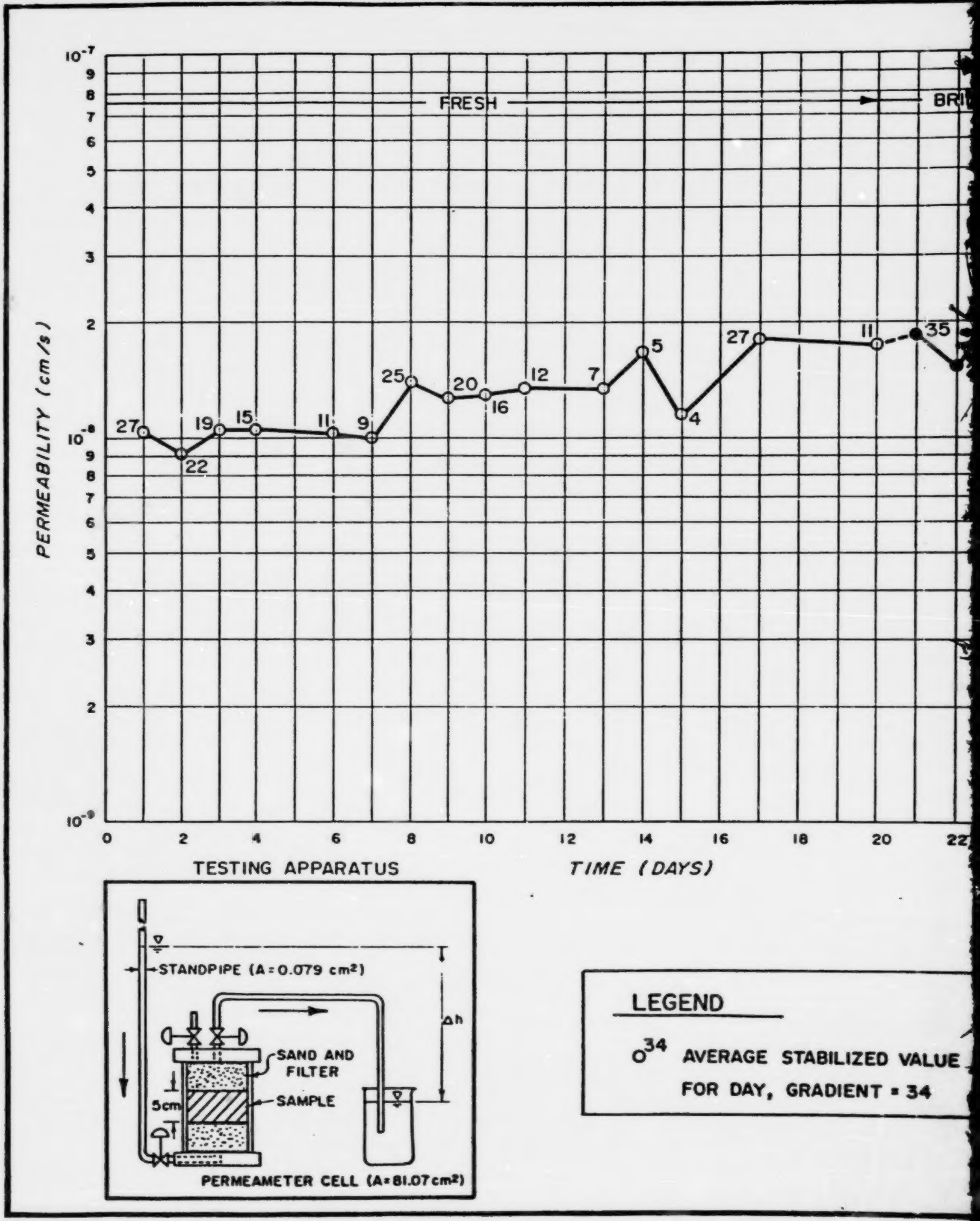
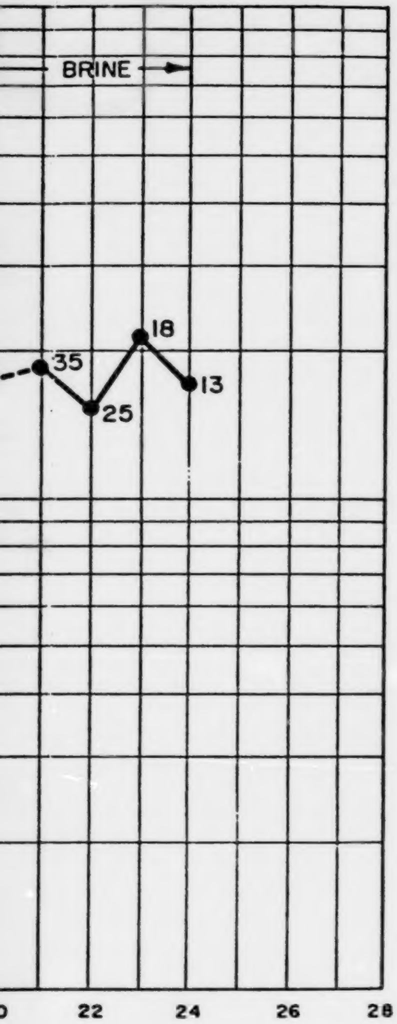


Figure 19. Falling head permeability, Test No. 4.



VALUE
= 34

TEST No. 4

SAMPLE No.: I
SAMPLE TYPE: UNCONT.
MOULDING LIQUID: BRINE SOAK
PERMEANT: FRESH/BRINE

INITIAL MATERIAL PROPERTIES

	% Passing 75μ	% Passing 2μ	W_L	W_P	P.I.
CLASSIFICATION	54	28	20.2	16.6	3.6

	% Clay Minerals	Clay Components
SEM	9	SMECTITE : 32 % ILLITE : 36 % KAOLINITE : 23 %

COMPONENT	[Cl⁻] mg/L	[Na⁺] mg/L	SAR
INITIAL PORE FLUID CHEMISTRY	48 HR. BRINE SOAK	—	—
BRINE PERMEANT AND MOULDING	220,000	135,000	1473
FRESH WATER PERMEANT	3	3	0.09

COMPACTION PROPERTIES

	Moisture Content, w(%)	Dry Density, γ_D, (kg/m^3)
STANDARD PROCTOR	13.4	1875
START OF TEST	16.2	—
END OF TEST	20.9	—

JOB No. 989

ALBERTA ENVIRONMENT
BRINE-CLAY LINER INTERACTION STUDY
FALLING HEAD PERMEABILITY
TEST No. 4

KOMEX	APPROVED	DATE APR./85	FIG. 19

It is noted that the difference between tests #3 and #4 is the brine soaking, which does not appear to have had a significant influence on permeability. The initial permeabilities are similar, in the order of 1×10^{-8} cm/sec.

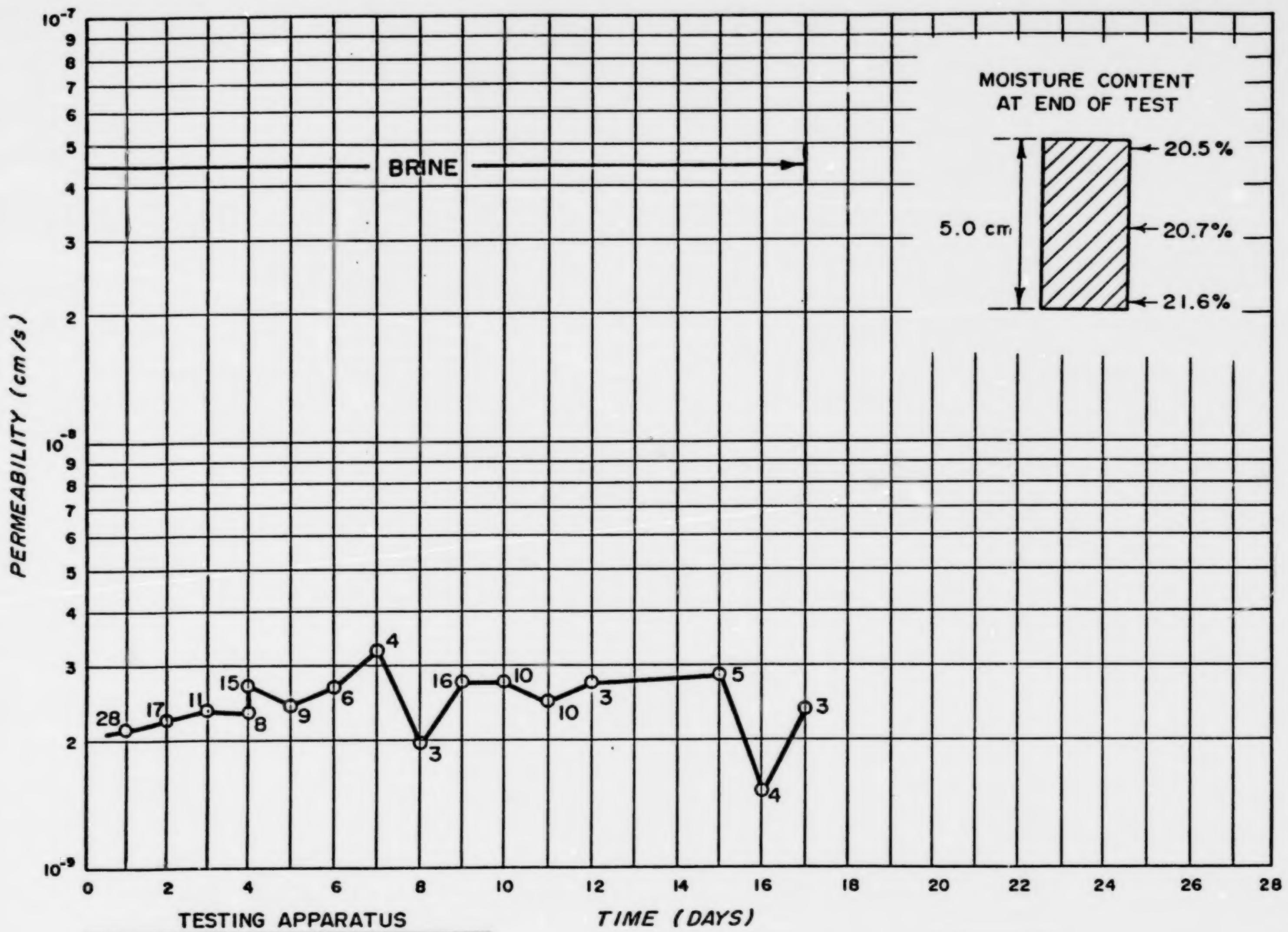
Test #5: Brine Soak/Brine: Test # 5 was prepared by soaking uncontaminated material with brine for 48 hours then permeating with brine. This represents a situation where natural materials are pretreated by soaking with brine immediately before the brine pond goes into service. The purpose of pretreating with brine is to allow preshrinkage of the clay prior to compaction so that the permeability changes due to brine permeation will be greatly reduced.

In Test #5 the uncontaminated Sample #1 was soaked for 48 hours with hypersaline brine, then permeated with a brine solution. The results of this test are shown in Figure 20 and, once again, indicate a relatively constant permeability with time. It is noted that in this test the final saturation of the sample is about 92%, which is close to the initial saturation. The sample changes in moisture content by less than 1%. The lower permeability for test #5 as compared with tests #3 and #4 is likely a reflection of the partial saturation of the material rather than brine soaking.

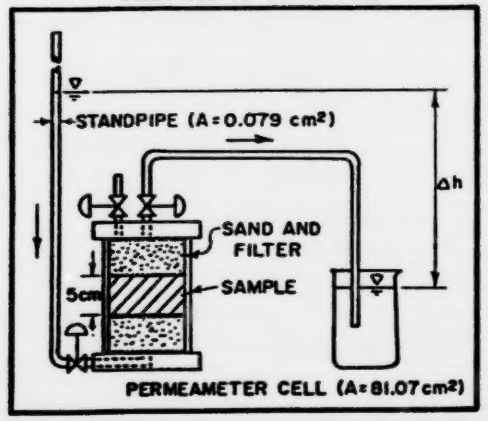
3.6.2 Type 2 - Compacted, Brine-Contaminated Clay Till

A total of five tests were conducted on samples of brine-saturated clay till collected from the pond bottom. The materials were subjected to brine fluids for at least five years and thus represent the "long-term" effect that brine may have on both the clay mineralogy and the hydraulic response.

Test #6: Fresh/Fresh-Brine: In Test #6, the contaminated clay till from Sample #2 was prepared by recompacting with a fresh moulding fluid, then was permeated with fresh water followed by brine. This test represents a situation where the pore fluid electrolyte concentration is diluted, as may occur where fresh water permeates a previously brine-saturated material. The results of Test #6 are summarized in Figure 21, and indicate that the



TESTING APPARATUS



LEGEND

o34 AVERAGE STABILIZED VALUE FOR DAY, GRADIENT = 34

TEST No. 5

SAMPLE No.: I
SAMPLE TYPE: UNCONT.
MOULDING LIQUID: BRINE SOAK
PERMEANT: BRINE

INITIAL MATERIAL PROPERTIES

	% Passing 75μ	% Passing 2μ	W_L	W_P	P.I.
CLASSIFICATION	55	29	20.2	16.6	3.6

	% Clay Minerals	Clay Components
SEM	9	SMECTITE : 32 % ILLITE : 36 % KAOLINITE : 23 %

COMPONENT	[Cl⁻] mg/L	[Na⁺] mg/L	SAR
INITIAL PORE FLUID	48 HR. BRINE SOAKED		
BRINE PERMEANT AND MOULDING	220,000	135,000	1473

COMPACTION PROPERTIES

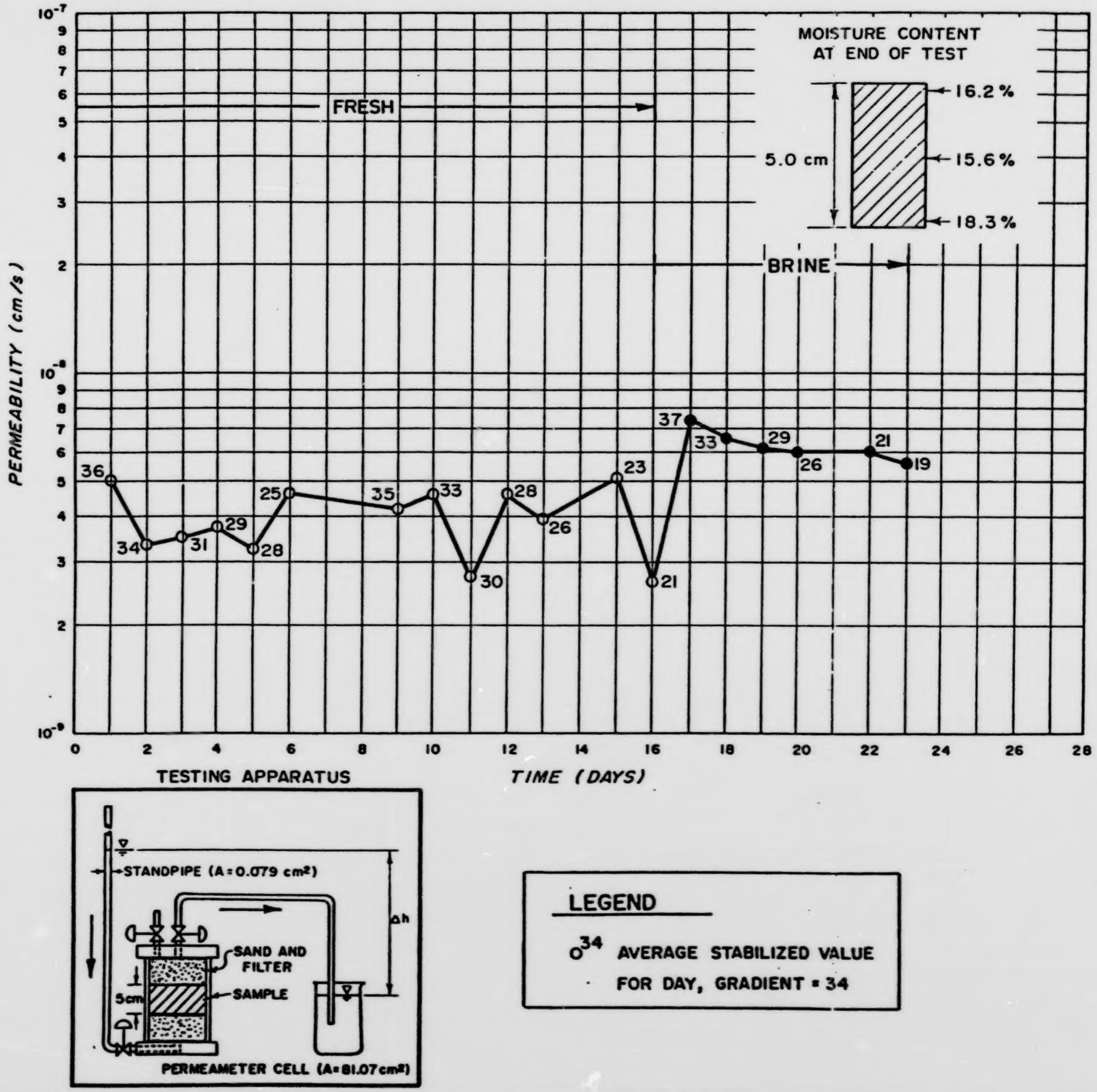
	Moisture Content, w(%)	Dry Density, γ_D, (kg/m³)
STANDARD PROCTOR	13.4	1875
START OF TEST	16.7	—
END OF TEST (AVER.)	17.0	—

JOB No. 989

ALBERTA ENVIRONMENT
BRINE-CLAY LINER INTERACTION STUDY.
FALLING HEAD PERMEABILITY
TEST No. 5

KOMEX
APPROVED
DATE APR. /85
FIG. 20

Figure 20. Falling head permeability, Test No. 5.



TEST No. 6

SAMPLE No.: 2	SAMPLE TYPE : CONTAMINATED
MOULDING LIQUID: FRESH	PERMEANT : FRESH / BRINE

INITIAL MATERIAL PROPERTIES

	% Passing 75μ	% Passing 2μ	W_L	W_P	P.I.
CLASSIFICATION	57	29	37.0	23.1	13.9

	% Clay Minerals	Clay Components
SEM	13	SMECTITE : 42 % ILLITE : 31 % KAOLINITE : 20 %

COMPONENT	[Cl⁻] mg/L	[Na⁺] mg/L	SAR
INITIAL PORE FLUID CHEMISTRY	38,000	25,200	726
BRINE PERMEANT	220,000	135,000	1473
FRESH WATER PERMEANT AND MOULDING	3	3	0.09

COMPACTION PROPERTIES

	Moisture Content, w(%)	Dry Density, γ_D,(kg/m³)
STANDARD PROCTOR	13.6	1869
START OF TEST	14.9	1845
END OF TEST (AVER.)	16.7	1798

ALBERTA ENVIRONMENT
BRINE-CLAY LINER INTERACTION STUDY
FALLING HEAD PERMEABILITY
TEST No. 6
JOB No. 989
KOMEX
APPROVED
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FIG. 21

Figure 21. Falling head permeability, Test No. 6.

permeability to fresh water is relatively constant at 4 x 10^{-9} cm/sec and that the introduction of brine tends to increase the permeability to about 6 x 10^{-9} cm/sec. It should be noted that in test #6, the final saturation state is close to 100%, and the sample increased in moisture by about 2%. It is noted that the stabilized permeability for this test is lower than that of tests #3 and #4, which represent the same moulding and permeation conditions; however, the sample for tests #3 and #4 was originally uncontaminated, whereas the sample used in test #6 had been subjected to brine for five years.

Test #7: Brine/Brine: Test #7 was conducted on material from Block Sample #2, and was exposed to brine for a five-year period. The moulding fluid was brine and the permeant was brine. The falling head permeability test results are summarized in Figure 22 and indicates that the initial pore fluid has a much lower concentration than the hypersaline brine. Thus, mixing brine as a moulding fluid would tend to increase the initial salt concentration in the sample. The summary of data in Table 17 indicates that the sample saturation remained relatively constant at about 95% and the overall moisture content of the sample decreased by about 0.8%.

The falling head permeability test results in Figure 22 indicate a general trend of decreasing permeability with time. This result may reflect unstable readings due to partial saturation rather than clay-brine interaction. Alternatively, this trend could be a reflection of the shrinkage of the bound layer around clay minerals, leading to mobility of clay particles in the aggregate structure. Mobile clay particles could plug smaller pores and hence reduce permeability as particle migration progresses.

Test #8: Brine/Brine: Test #8 was conducted on contaminated material from Block Sample #3. Brine was used as the moulding fluid and the permeant. Again, the initial pore fluid had a salt concentration well below that of the brine and hence the use of brine as a moulding liquid tended to increase the pore fluid

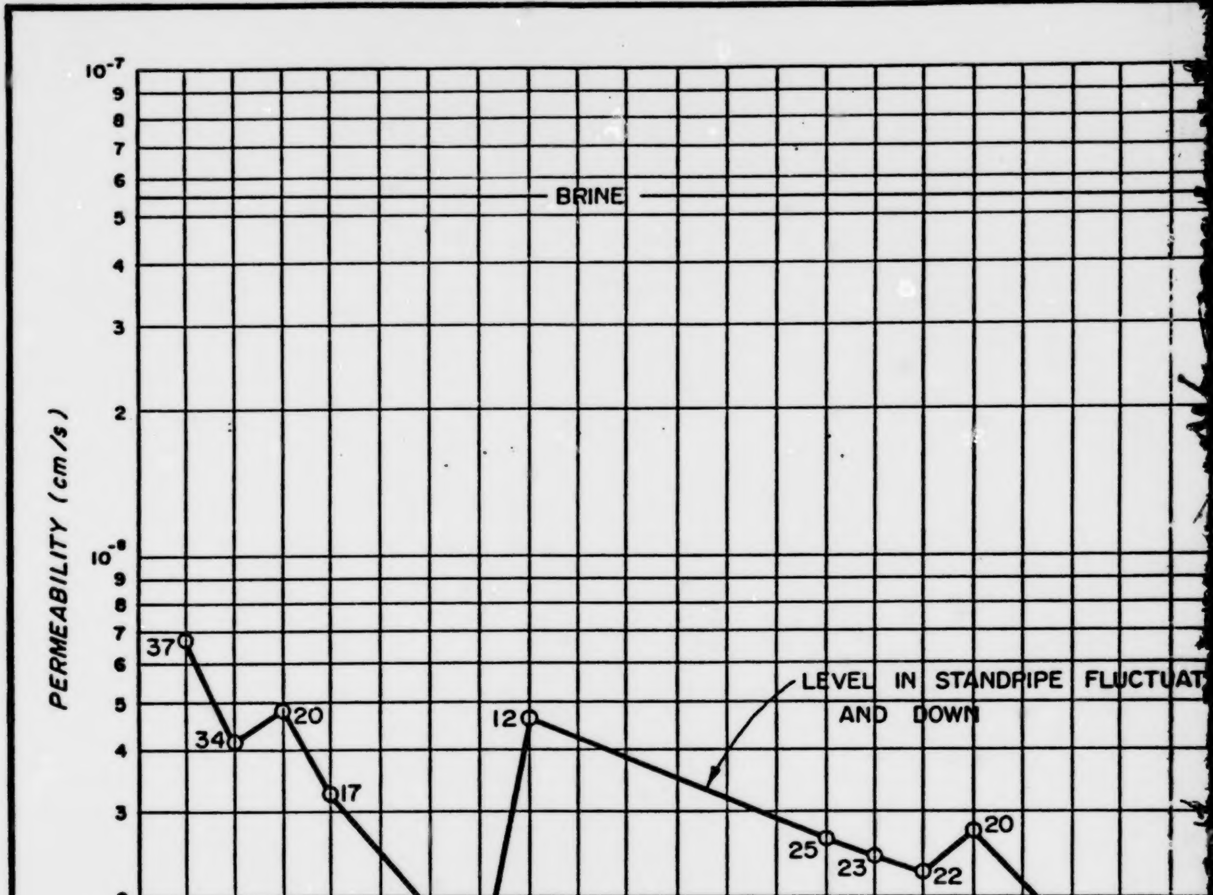
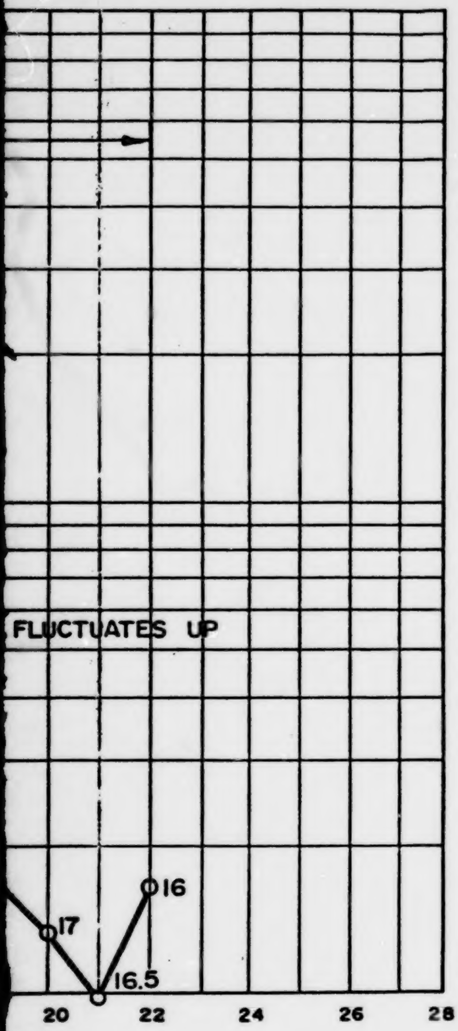


Figure 22. Falling head permeability, Test No. 7.



IZED VALUE
ENT = 34

TEST No. 7

SAMPLE No.: 2 SAMPLE TYPE : CONTAMINATED

MOULDING LIQUID: BRINE PERMEANT : BRINE

INITIAL MATERIAL PROPERTIES

	% Passing 75μ	% Passing 2μ	W_L	W_P	P.I.
CLASSIFICATION	73	36	25.9	19.0	6.9

	% Clay Minerals	Clay Components
SEM	13	SMECTITE : 42 % ILLITE : 31 % KAOLINITE : 20 %

COMPONENT	$[Cl^-]$ mg/L	$[Na^+]$ mg/L	SAR
INITIAL PORE FLUID CHEMISTRY	38,000	25,000	726
BRINE PERMEANT	220,000	135,000	1473

COMPACTION PROPERTIES

	Moisture Content, w(%)	Dry Density, γ_D,(kg/m³)
STANDARD PROCTOR	13.8	1874
START OF TEST	22.5	1565
END OF TEST (AVER.)	21.7	1595

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ALBERTA ENVIRONMENT

BRINE-CLAY LINER INTERACTION STUDY

FALLING HEAD PERMEABILITY
TEST No. 7

KOMEX	APPROVED	DATE APR. /85	FIG. 22

concentration. This test represents a condition wherein brine soaked material is recompacted, then permeated with brine.

The results of the test are shown in Figure 23 and indicate a relatively stable permeability over a 24-day testing period. As indicated in Table 17, the initial saturation increases to just over 100%, representing an increase in moisture content of 8% during testing. The main difference between tests #8 and #6 (both are saturated during testing) is the moulding fluid and permeant. The introduction of brine appears to have increased the permeability by about half an order of magnitude (test #8) as compared to moulding and permeating with fresh water (test #6). This is likely due to flocculating tendencies in test #8, compared to dispersion in test #6.

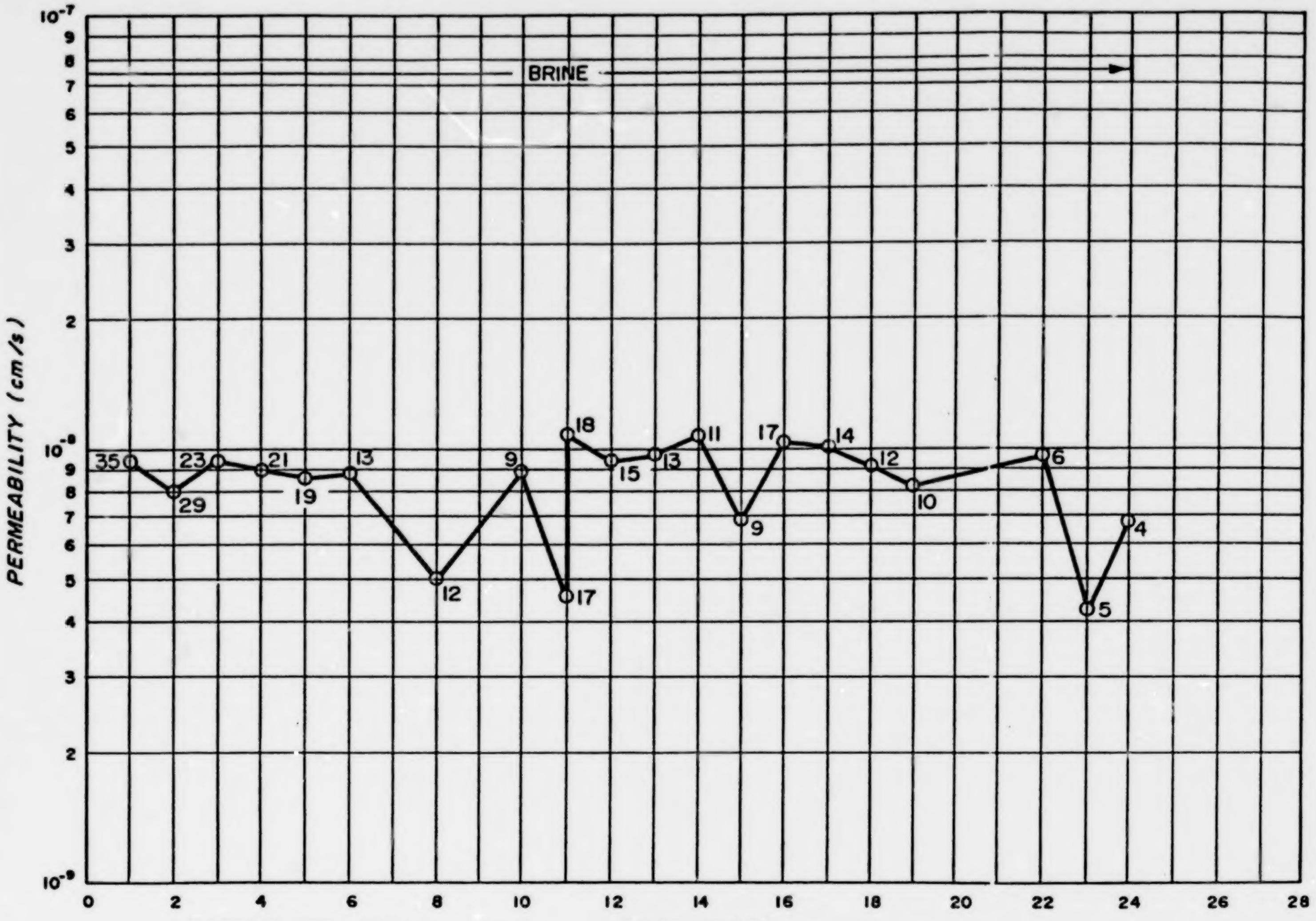
3.6.3 Type 3 - "Undisturbed" Contaminated Clay Till

Falling head permeability tests were conducted on Shelby tube samples cut from the block samples of the liner. The tests were conducted with brine as a permeant and the material was as close to the in situ state of compaction and moisture as possible. The results of the tests on samples #2 and #3 are reported as tests #9 and #10 in figures 24 and 25, respectively.

The results of these tests indicate a relatively stable permeability over a short duration of testing in the range of 1 x 10^{-7} to 2 x 10^{-7} cm/sec. These tests are comparable to test #1, except the sample was field-compacted and subject to brine permeation for 5 years (initially) rather than just 3 days (lab test duration). It should be noted that the permeability scales in figures 24 and 25 are different from the previous scales for tests #1 through 8.

3.6.4 Type 4 - Compressibility Test on "Undisturbed" Contaminated Clay Till

A consolidation test was conducted on an "undisturbed" sample cut from Block Sample #2 from the pond bottom. The cell fluid was hypersaline brine. The results of the vertical stress



TEST No. 8

SAMPLE No.: 3	SAMPLE TYPE : CONTAMINATED
MOULDING LIQUID: BRINE	PERMEANT : BRINE

INITIAL MATERIAL PROPERTIES

	% Passing 75μ	% Passing 2μ	W_L	W_P	P.I.
CLASSIFICATION	61	32	24.9	17.8	7.1

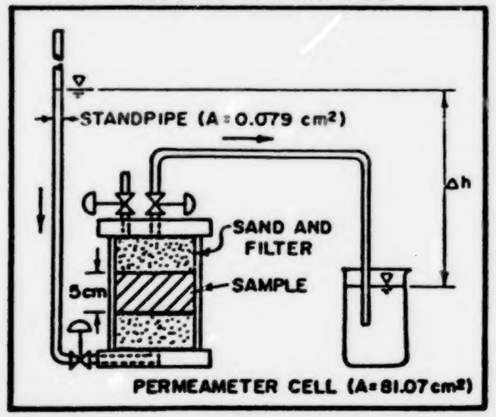
	% Clay Minerals	Clay Components
SEM	NOT TESTED	———

COMPONENT	[Cl⁻] mg/L	[Na⁺] mg/L	SAR
PORE FLUID CHEMISTRY	53,000	34,800	796
BRINE PERMEANT	220,000	135,000	1473

COMPACTION PROPERTIES

	Moisture Content, w(%)	Dry Density, γ_D, (kg/m³)
STANDARD PROCTOR	13.8	1874
START OF TEST	16.0	1800
END OF TEST	22.0	1580

TESTING APPARATUS

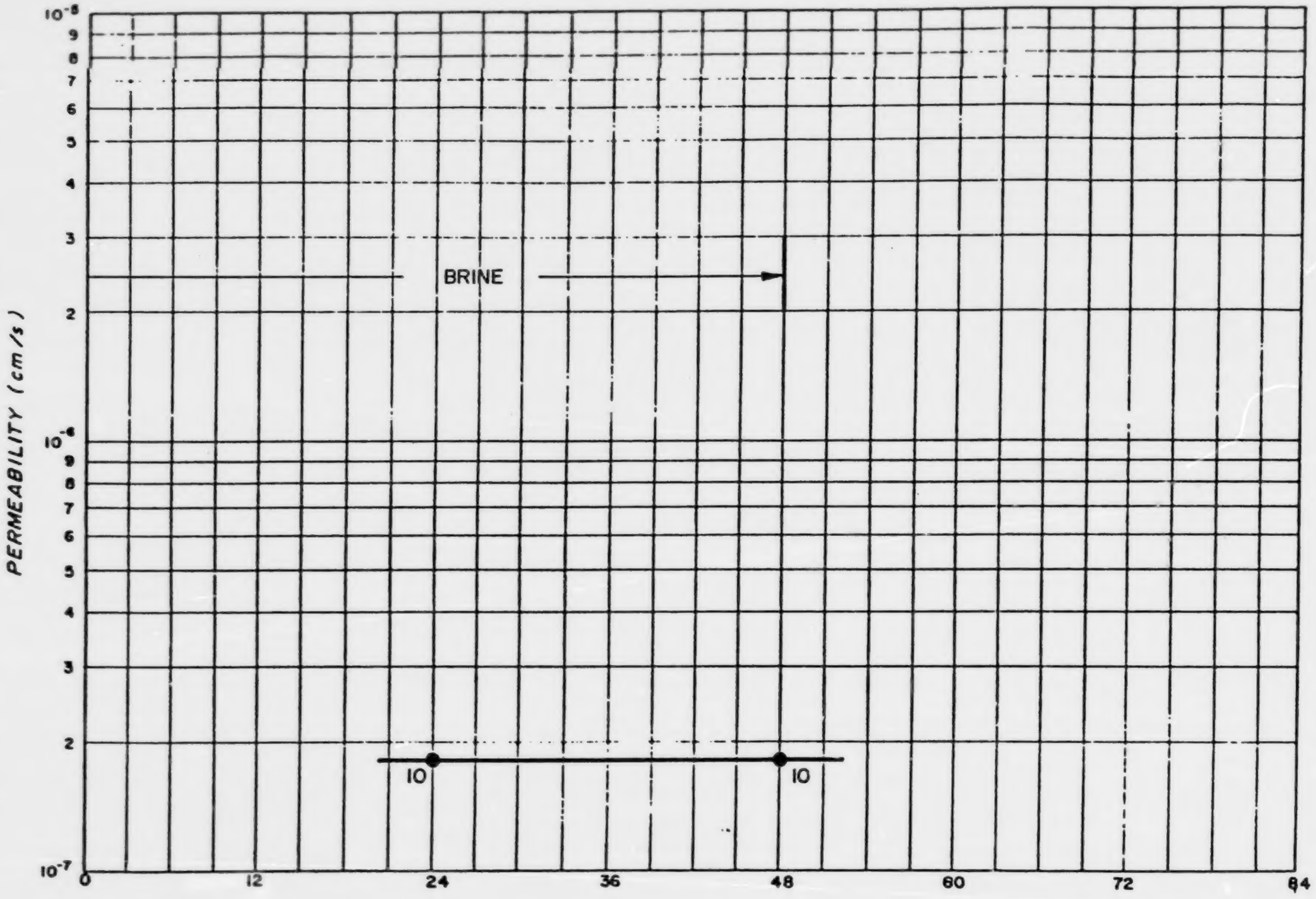


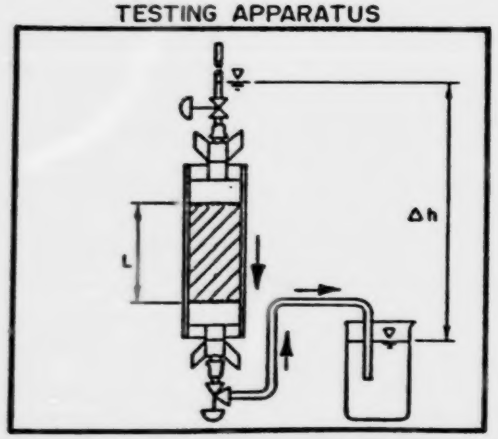
LEGEND

$\circ^{34}$ AVERAGE STABILIZED VALUE FOR DAY, GRADIENT = 34

ALBERTA ENVIRONMENT
BRINE-CLAY LINER INTERACTION STUDY
FALLING HEAD PERMEABILITY
TEST No. 8
JOB No. 989
KOMEX | APPROVED | DATE APR. /85 | FIG. 23

Figure 23. Falling head permeability, Test No. 8.





LEGEND

$\circ^{34}$ AVERAGE STABILIZED VALUE FOR DAY, GRADIENT = 34

TEST No. 9

SAMPLE No.: 2
SAMPLE TYPE: CONTAMINATED UNDISTURBED
MOULDING LIQUID: ———
PERMEANT: BRINE

INITIAL MATERIAL PROPERTIES

	% Passing 75μ	% Passing 2μ	W_L	W_P	P.I.
CLASSIFICATION	60	26	26	19	7

	% Clay Minerals	Clay Components
SEM	13	SMECTITE : 42 % ILLITE : 31 % KAOLINITE : 20 %

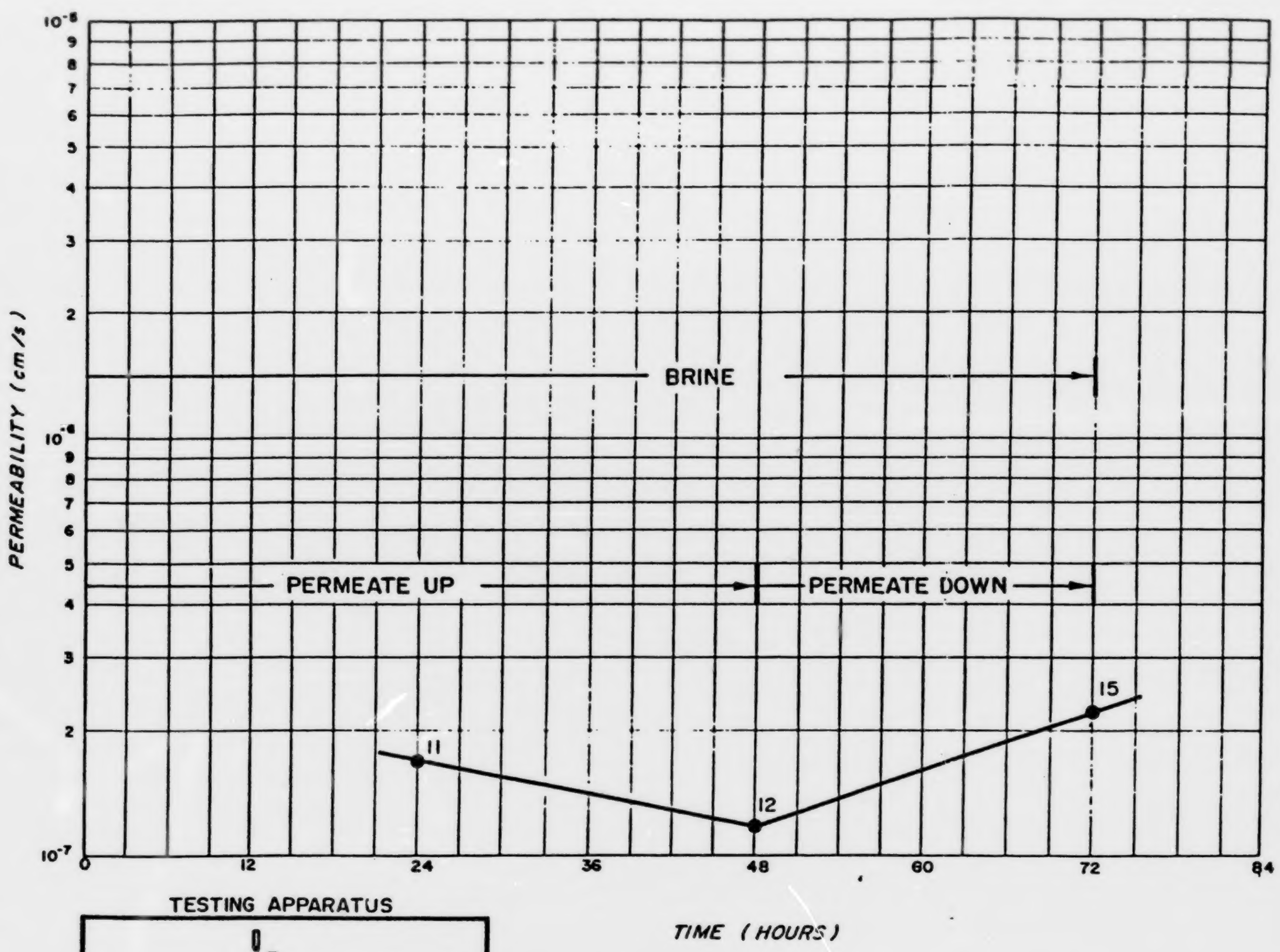
COMPONENT	[Cl⁻] mg/L	[Na⁺] mg/L	SAR
PORE FLUID CHEMISTRY	38,000	25,200	726
BRINE PERMEANT	220,000	135,000	1473

NOTE:

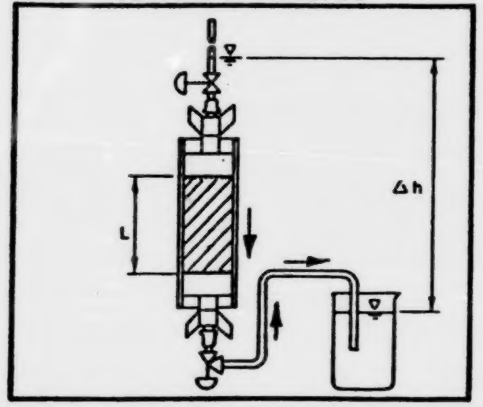
1. TESTS CONDUCTED ON "UNDISTURBED" SAMPLES OBTAINED BY PUSHING 3" Ø SHELBY TUBE INTO BLOCK SAMPLE No. 2

ALBERTA ENVIRONMENT
BRINE-CLAY LINER INTERACTION STUDY
FALLING HEAD PERMEABILITY
TEST No. 9
JOB No. 989
KOMEX
APPROVED
DATE APR./85
FIG. 24

Figure 24. Falling head permeability, Test No. 9.



TESTING APPARATUS



LEGEND

$\circ^{34}$ AVERAGE STABILIZED VALUE FOR DAY, GRADIENT · 34

TEST No. 10

SAMPLE No.: 3

SAMPLE TYPE: CONTAMINATED, UNDISTURBED

MOULDING LIQUID: ———

PERMEANT: BRINE

INITIAL MATERIAL PROPERTIES

	% Passing 75μ	% Passing 2μ	W_L	W_P	P.I.
CLASSIFICATION	60	26	25	18	7

	% Clay Minerals	Clay Components
SEM	——— NOT	TESTED ———

COMPONENT	[Cl⁻] mg/L	[Na⁺] mg/L	SAR
PORE FLUID CHEMISTRY	53,000	34,800	796
BRINE PERMEANT	220,000	135,000	1473

NOTE:

1. TESTS CONDUCTED ON "UNDISTURBED" SAMPLES OBTAINED BY PUSHING 3" Ø SHELBY TUBE INTO BLOCK SAMPLE No. 3

JOB No. 985

ALBERTA ENVIRONMENT			
BRINE-CLAY LINER INTERACTION STUDY			
FALLING HEAD PERMEABILITY TEST No. 10			
KOMEX	APPROVED 7.13C	DATE APR./85	FIG. 25

Figure 25. Falling head permeability, Test No. 10.

versus void ratio and calculated permeability are presented in Figure 26. It is interesting to note that the calculated permeabilities from this test are within the range of the "undisturbed" falling head permeability tests presented as tests #9 and #10 in figures 24 and 25, respectively.

3.7 SUMMARY OF PERMEABILITY TESTING PROGRAM

The results of the falling head permeability tests conducted on recompacted samples of uncontamined and brine-contaminated clay till are summarized in figures 27 and 28, respectively. The results can be summarized as follows:

1. Saturation level appears to have a marked influence on permeability as measured by the falling head permeability test;
2. The permeabilities for partially saturated conditions are lower than for fully saturated conditions;
3. Regardless of saturation, the effect of introducing brine to an uncontaminated sample prepared with fresh moulding water is to increase the permeability by about one order of magnitude, as indicated by permeability test #1 in Figure 27;
4. Tests conducted with brine as a permeant generally had permeabilities higher than tests with fresh water as permeant; however, the differences are very small and could also be attributed to variations in sample compaction and/or clay content;
5. Samples of uncontaminated material prepared with a brine moulding fluid generally had permeabilities higher than recompacted samples of brine-contaminated clay (compare tests #3 and #4 in Figure 27 with tests #6 and #8 in Figure 28);
6. Brine soaking appears to have only a small influence on permeability as compared to tests on samples prepared with brine fluid but without brine soaking;

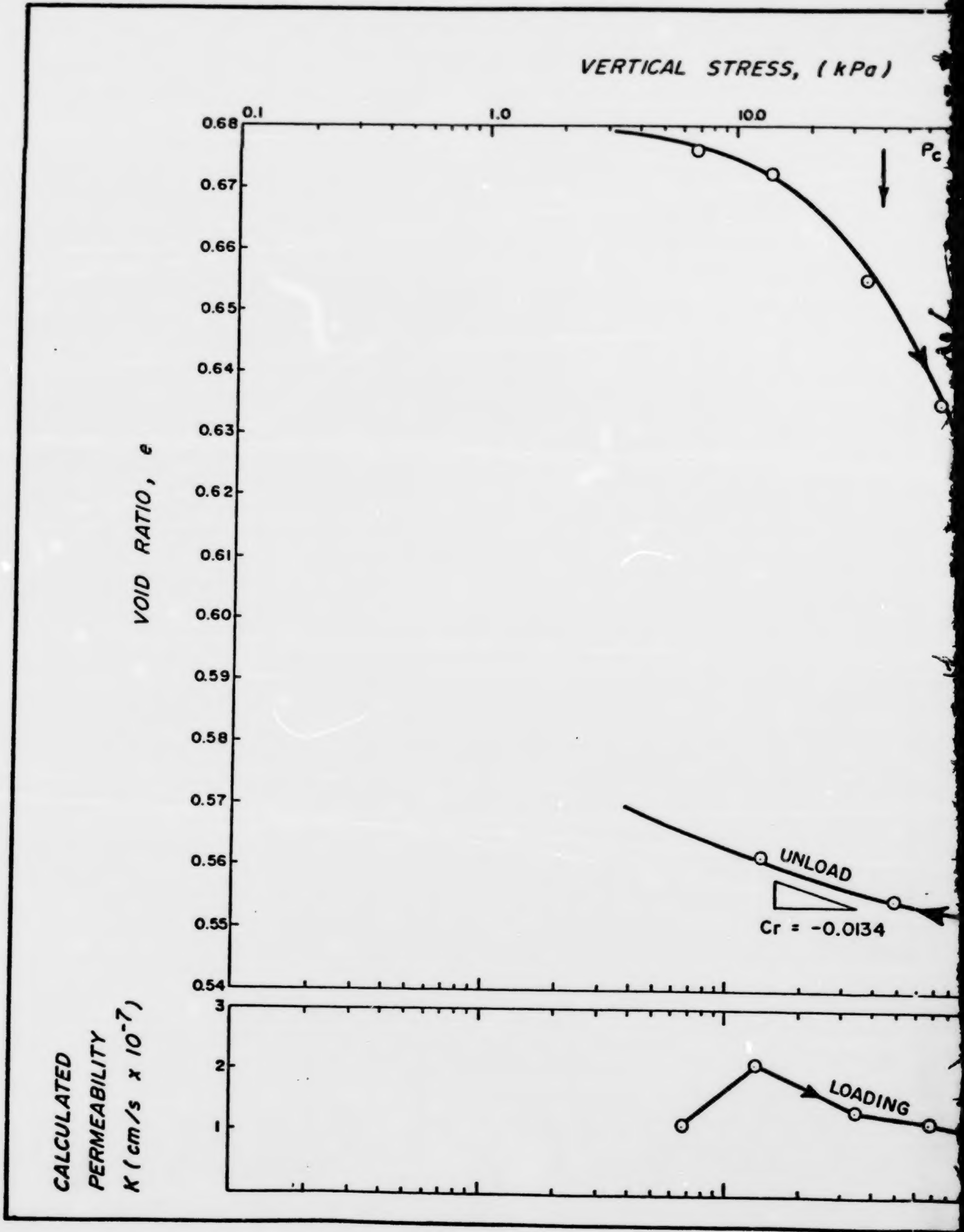
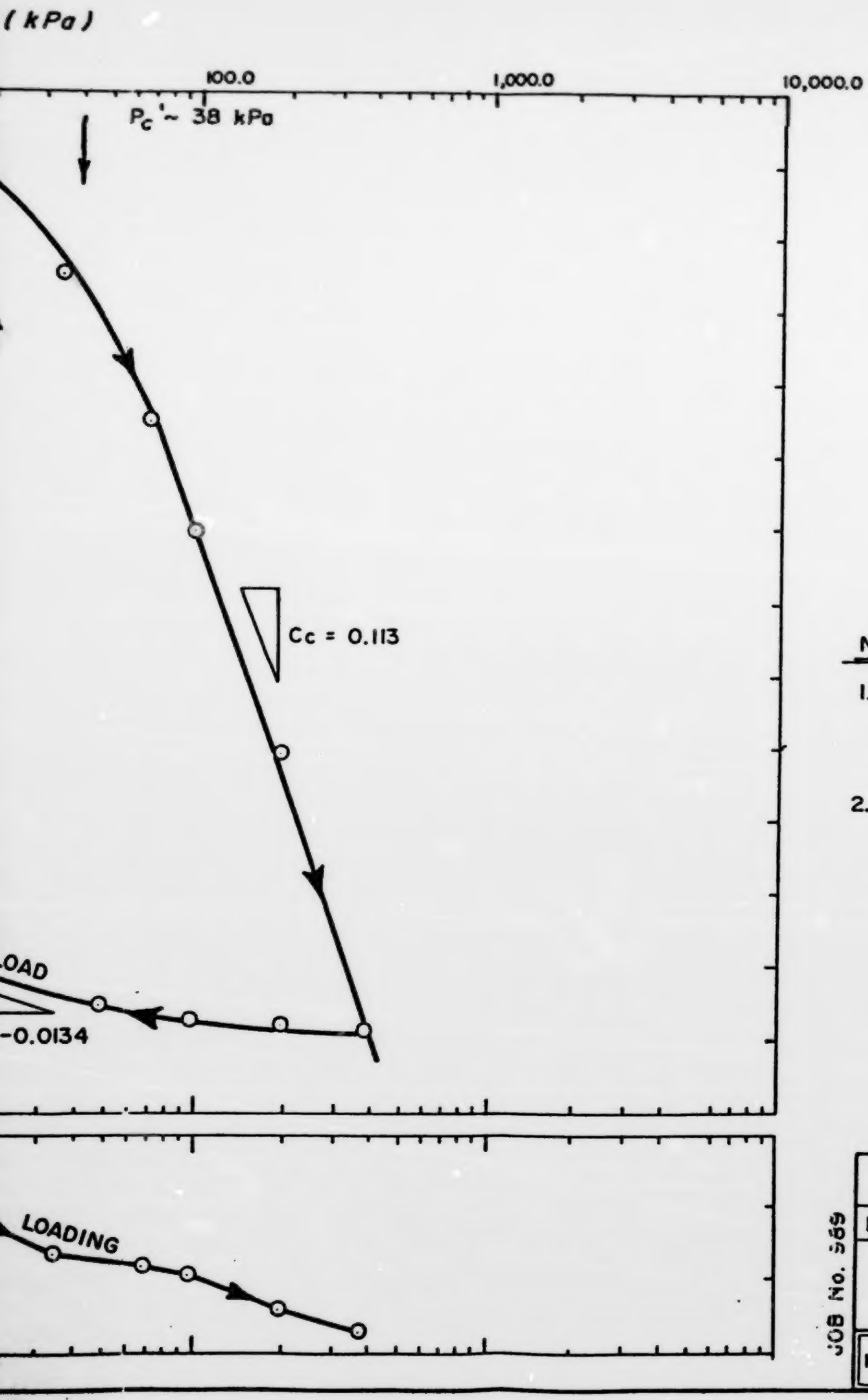


Figure 26. Consolidation test on Sample 2.



NOTES:

1. TEST ON "UNDISTURBED" SAMPLE CUT FROM BLOCK OF SAMPLE 2 (POND BOTTOM)
2. CELL FLUID - BRINE

JOB No. 569

ALBERTA ENVIRONMENT

BRINE - CLAY LINER INTERACTION STUDY

CONSOLIDATION TEST
ON SAMPLE 2

KOMEX	APPROVED RBC	DATE APR. / 85	FIG. 26

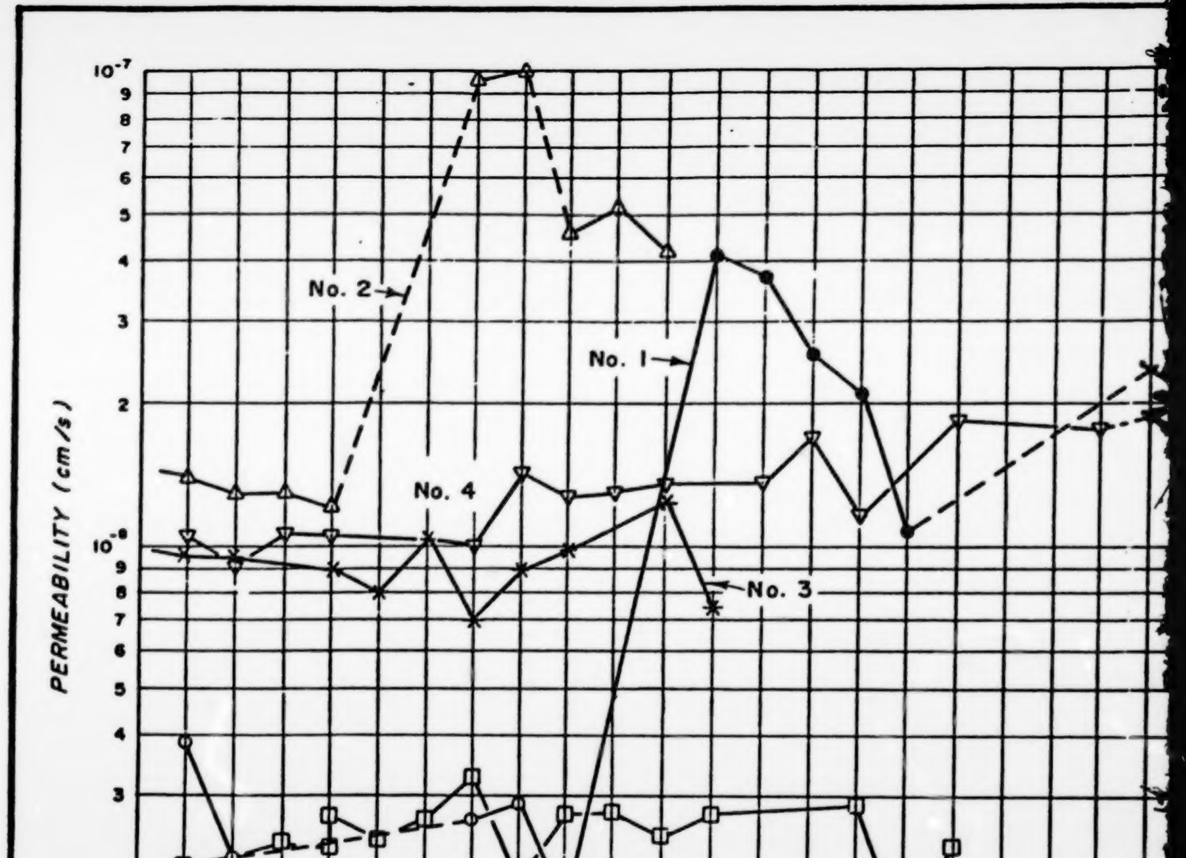
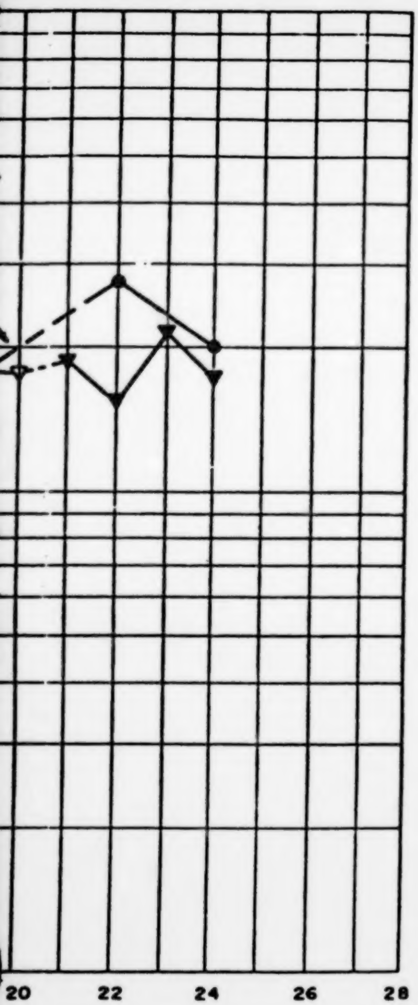


Figure 27. Summary of permeability tests - uncontaminated sampl



RECOMPACTED SAMPLES OF
UNCONTAMINATED CLAY TILL

LEGEND

TEST		SAMPLE No.	MOULDING FLUID	PERMEANT
○	1[a]	1	FRESH	FRESH, THEN BRINE
△	2[a]	1	BRINE	BRINE
✱	3	1	BRINE	FRESH
▽	4[a]	1	BRINE (SOAKED 48 HRS.)	FRESH, THEN BRINE
□	5	1	BRINE (SOAKED 48 HRS.)	BRINE

(a) SATURATION LEVEL BELOW 100 % AT END OF TEST, SMALL INCREASE IN OVERALL MOISTURE CONTENT OF SAMPLE.

JOB No. 989

ALBERTA ENVIRONMENT

BRINE-CLAY LINER INTERACTION STUDY

SUMMARY OF PERMEABILITY
TESTS-UNCONTAMINATED SAMPLE

KOMEX	APPROVED	DATE	
		APR. /85	FIG. 27

ample.

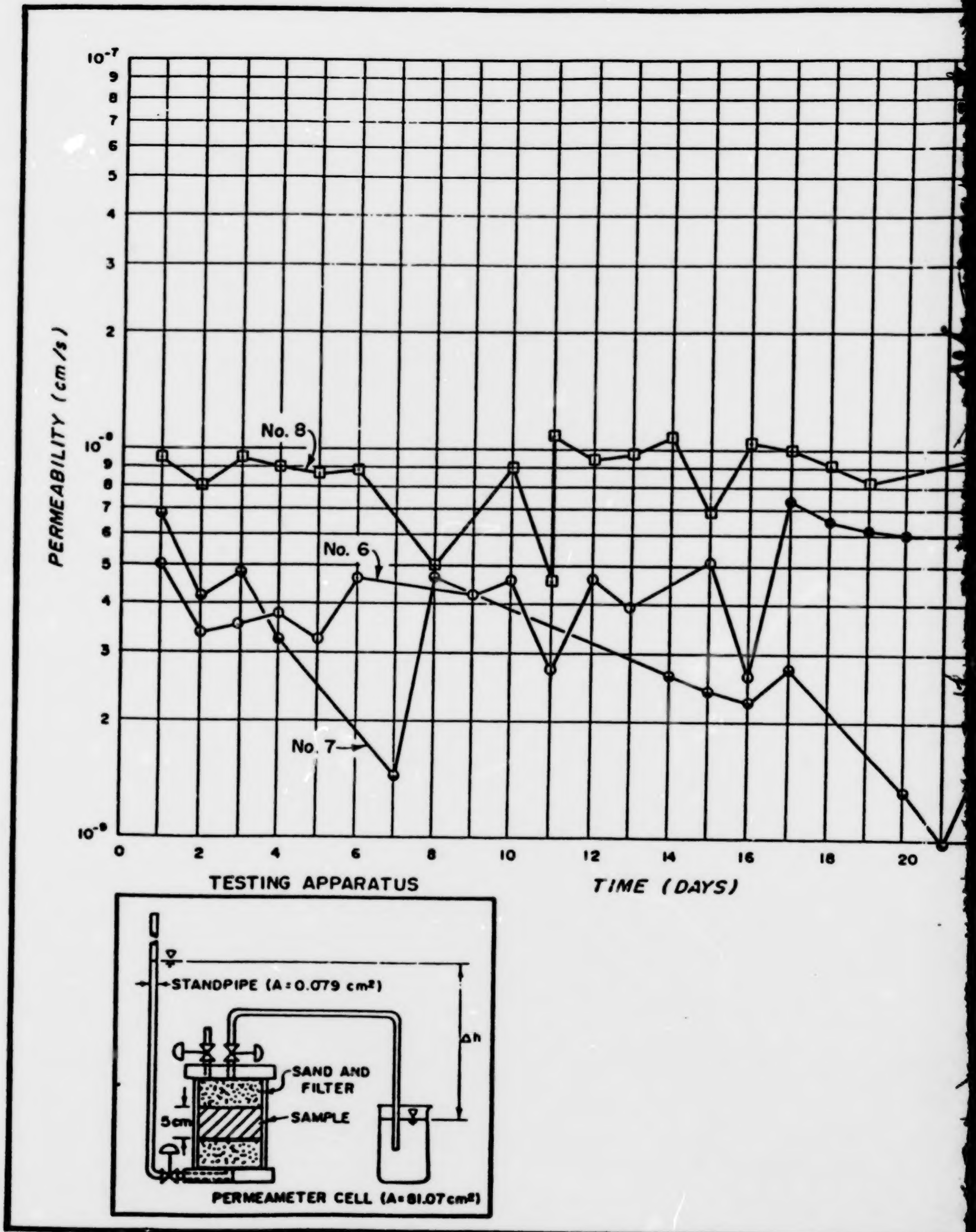
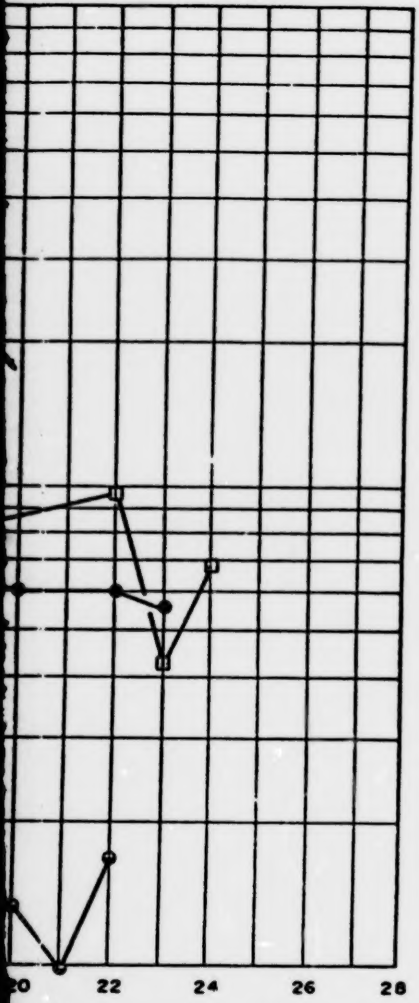


Figure 28. Summary of permeability tests - brine contaminated sa



RECOMPACTED SAMPLES OF
BRINE CONTAMINATED CLAY TILL

LEGEND

TEST	SAMPLE No.	MOULDING FLUID	PERMEANT
○ 6	2	FRESH	FRESH, THEN BRINE
● 7(a)	2	BRINE	BRINE
□ 8	3	BRINE	BRINE

(a) SATURATION LEVEL BELOW 100 % AT END OF TEST, SMALL DECREASE IN OVERALL MOISTURE CONTENT

ALBERTA ENVIRONMENT
BRINE-CLAY LINER INTERACTION STUDY
SUMMARY OF PERMEABILITY
TESTS-BRINE CONTAMINATED SAMPLES
JOB No. 989
KOMEX | APPROVED 7BC | DATE APR. /85 | FIG. 28

d sample.

7. The interaction of brine and clay appears to occur rapidly as demonstrated by the Atterberg Limit test results;
8. The introduction of a fresh water permeant to a sample with brine as a moulding fluid tends to have only a small influence on permeability;
9. All of the recompacted samples permeated with brine have permeabilities at least one order of magnitude lower than tests on "undisturbed" material permeated with brine (compare results in figures 27 and 28 with the results in figures 24 to 26); and
10. The influence of changes in the concentration of the permeant appear to occur rapidly, even though the passage of fluid through the sample over a short period of time is negligible.

4. EVALUATION AND COMPARISON OF RESULTS

The results of the falling head permeability tests on samples of the Procor clay till liner are compared with other reported literature in Table 18. This comparison of results indicates that the observed changes are within the ranges of other reported permeability changes.

The sources of error in permeability testing listed previously in Table 1 indicate a wide range in measured hydraulic conductivity due to several factors. Of the factors listed in Table 1, partial saturation of the system (air in the sample) and changes in the concentration of the permeant are the most important factors to be considered in the testing program described in this report. The saturation condition of samples listed in Table 17 indicates that several of the tests were conducted on partially saturated materials. By comparing the test results on fully saturated samples, the effects on permeability of permeant and moulding fluid changes can be assessed. A comparison of the permeability test results for saturated samples is shown in Figure 29. These results indicate that permeability tests on "undisturbed" brine-contaminated clay till sampled from the pond bottom were one order of magnitude higher than recompacted samples in the laboratory. With regard to the recompacted samples, initially uncontaminated till samples with a brine moulding liquid had a higher permeability than brine-contaminated samples (that is, samples in the pond bottom that were exposed to brine for about five years had lower permeabilities than the fabricated tests). Additionally, the permeability test results on partially saturated samples indicated that the effect of introducing brine into an uncontaminated sample with a fresh moulding water was to increase the permeability by up to one order of magnitude.

The evaluation of field performance at the Procor pond, discussed in Section 8.2, indicates that the most probable in situ permeability of the liner is in the order of 2×10^{-6} cm/sec. It is noted that this estimate is one order of magnitude higher than

Table 18. Summary of reported literature on clayey soils - brine interaction and changes in permeability.

Case Record	Sample Type	% Clay Size	Plastic Index	Clay Content			Compaction	Permeant	Change in Permeability Due to Brine Introduction
				% Smectite	% Kaolinite	% Illite			
				(% by weight in sample)					
IOL, Redwater (EBA 1978)	from pond liner	21	12	6 to 9	4 to 8	6 to 7	wet of optimum	distilled water	1 order of magnitude
IOL, Redwater (Hudec 1979)	uncontaminated material	ND[a]	ND	ND	ND	ND	ND	brine	increase 5 times
Chevron, Redwater (EBA 1978)	from pond bottom	46	15	ND	ND	ND	at optimum	distilled water	did not test, but lower than IOL
Dome, Ft. Sask. (Hardy 1977)	uncontaminated material	25 to 30	15 to 27	ND	ND	ND	2% wet of optimum	brine and distilled water	increase 20 times to 60 times
Saskatchewan Till (PFRA 1979)	uncontaminated material	32 to 36	10 to 24	ND	ND	ND	at optimum	brine	increase 5 times
Hardcastle and Mitchell (1976)	artificial	10	ND	ND	ND	10	sedimented	0.6 N salt solution	increase 1.2 times
McNeal and Coleman (1966)	natural clays	30	ND	10	ND	ND	sedimented	low conc. salt sol'n.	up to 1 order of magnitude

continued . . .

Table 18. Concluded.

Case Record	Sample Type	% Clay Size	Plastic Index	Clay Content % Smectite	 % Kaolinite	 % Illite	Compaction	Permeant	Change in Permeability Due to Brine Introduction
				(% by weight in sample)					
Procor, Redwater (present study)	from pond liner	25	-	4	3	5	2% wet of optimum	hypersaline brine	increase to 1.5 times to 5 times
Procor, Redwater (present study)	uncont. material	25	-	4	2	3	2% wet of optimum	hypersaline brine	up to 1 order of magnitude

[a] ND = No Data Available.

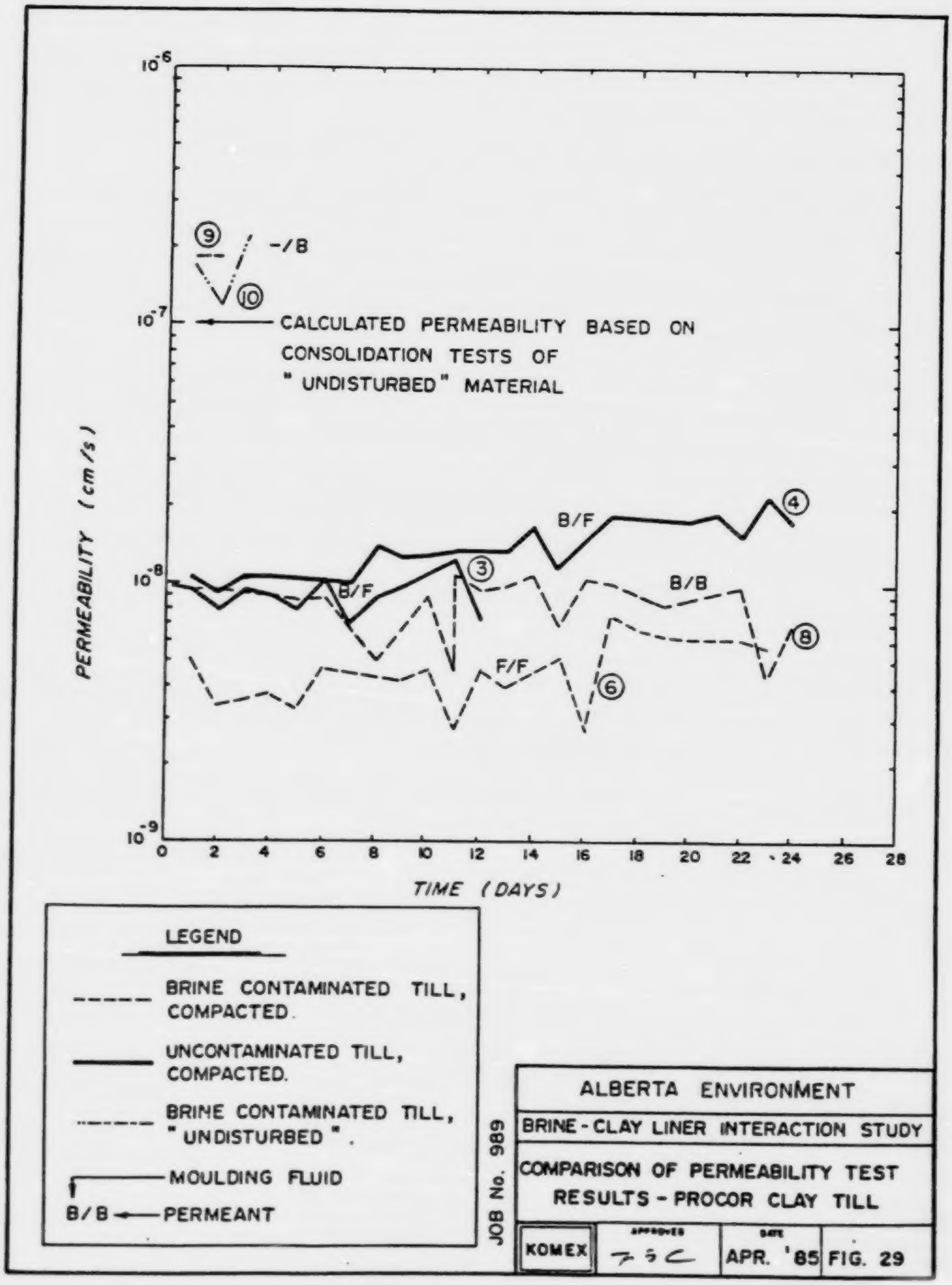


Figure 29. Comparison of permeability test results - Procor clay till.

the "undisturbed" permeability test results and two orders of magnitude higher than tests on recompacted samples as indicated in Figure 29. This wide variation in measured versus field permeability is similar to other reported case records (e.g., Olson and Daniel 1981). The order of magnitude difference between the field values and the measured values on "undisturbed" samples is most likely due to the crack formation in the field, which cannot be modelled in the laboratory on 5 cm to 10 cm diameter test samples.

The inherent difficulty in conducting laboratory tests to predict field permeability of compacted clay liners is relatively well established in the literature and further substantiated by the results of the tests presented in this report. However, regardless of the inability to predict field permeabilities, the effect of brine on compacted clay behaviour can be assessed by the results of this study. In this regard, and referring back to the questions posed in Section 1.1 of this report, the following comments can be made:

1. Long-Term Effect of Brine: The clay-brine interaction appears to be relatively rapid and a long-term (five-year) effect of brine on clay minerals and aggregate structure of compacted till appears to be insignificant compared with other factors affecting permeability.
2. Preconditioning to Minimize Shrinkage: The results of the tests on Procor liner materials indicate that preconditioning through soaking with brine does not have an appreciable influence on compacted permeability. However, soaking may aid in limiting crack formation in the field and thus could have an more important influence on field behaviour as opposed to laboratory measurements.
3. Laboratory Testing Procedures: The results of the tests on Procor liner materials indicate that uncontaminated, natural soil could be treated with brine solutions to model long-term brine soaking. The

results indicate the effect on measured permeability on recompacted samples of material soaked for five years in the field versus five days in the laboratory is about one-half an order of magnitude. Further, the observed differences in permeability could also be related to the sample preparation method, saturation, and the duration of the test.

The tests results reported herein and a review of published literature indicate that for compacted materials with a relatively low percentage of clay minerals, particularly smectite clay minerals, the effect on permeability of brine is within the range of permeability variations due to the inherent difficulties in conducting laboratory tests.

5. IMPLICATIONS FOR BRINE POND DESIGN

The results of this study indicate that for clay till materials having a similar mineralogical composition to the Procor liner, under worst case conditions, an order of magnitude increase in permeability could be anticipated in the field due to brine permeation. Further, the nature of operating conditions at brine ponds can lead to severe exposure of the liner to the elements and further affect field performance. Even without considering the effects of brine, field permeability is likely to be 1 to 3 orders of magnitude greater than laboratory permeability test values.

Based on the results of the literature review and testing program discussed in this report, the following points can be made in regard to implications for design of compacted clay till liners for brine ponds in Alberta:

1. For materials with a relatively low clay content and more particulary, a low percentage of smectite clay minerals, the worst case pond operating conditions lead to an order of magnitude increase in permeability due to clay - brine interaction.
2. A more important factor controlling the performance of liners is the adverse operating conditions at brine ponds. Fluctuating water levels lead to variations in temperature, and in the concentration of fluid permeating the liner. These adverse operating conditions could lead to an unserviceable liner regardless of the clay - brine interaction phenomenon.
3. With proper selection of materials to form the compacted clay liner and with design of an appropriate liner thickness and protective cover, it appears that the effect of clay - brine interaction can be accommodated in liner design. The most important factor controlling performance is the proper protection of the liner from temperature variations, and fluctuating moisture level. It is important to

recognize that protection of the clay liner to environmental conditions is a consideration for any clay lined facility.

4. The results of test #2 are hard to interpret; however, initial permeability values indicate that use of brine liquid as the moulding fluid may reduce the effects of subsequent brine permeation or clay structure. This is more effective than brine soaking alone, because it allows the clay to establish a stable structure during compaction (i.e., soil formation).

6. CONCLUSIONS

Based on the results of the study presented in this report, the following conclusions can be drawn:

1. A proper evaluation of the effectiveness of compacted clay materials for lining brine ponds requires an assessment of the characteristics of the clay minerals in the soil and the operating conditions of the pond.
2. Clay - brine interaction is a complex phenomenon for which several hypotheses have been advanced. Regardless of the physical or chemical reason for the interaction, the net effect is a reduction in volume of the clay minerals and hence, the sample. This reduction in volume leads to the opening of pore channels that could be manifested as cracks, which would increase permeability of the material.
3. A review of the literature indicates that permeability increases of up to one order of magnitude have been observed and/or predicted at brine ponds with compacted clay liners. These observations and predictions are consistent with the laboratory test results discussed in this report.
4. The laboratory test results on Procor clay till liner materials indicate that permeability tests on "undisturbed" materials are at least one order of magnitude higher than those of recompacted materials. The effect of brine soaking is small. The introduction of brine to a sample with fresh water moulding leads to a rapid increase in permeability of up to one order of magnitude. The introduction of fresh water to a sample with a brine moulding fluid is small.

5. A comparison of inferred field permeabilities with laboratory measured permeabilities indicates that the field permeabilities are at least one order of magnitude higher than those of laboratory tests on "undisturbed" samples. This result is consistent with other such comparisons reported in the literature.
6. The long-term effect of brine leachate on compacted clay till liners appears to be negligible in that the brine does not appear to degrade or appreciably alter the morphology of clay minerals or the fabric of the aggregate with time (at least based on SEM test results). However, shrinkage cracks do result that cause the increase in permeability.
7. Preconditioning material by soaking with brine appears to have a small influence on the recompacted samples from the Procor clay till liner. However, in the field, shrinkage could lead to crack formation, which could be limited through presoaking with brine. The effect of field crack formation could not be modelled in the laboratory.
8. It appears that uncontaminated samples of natural soil can be used to model the long term effects of brine saturation in the field. The difference in permeability of uncontaminated versus contaminated clay till from the Procor site was less than one-half an order of magnitude.
9. It appears that the most critical factor controlling permeability, and hence performance of a compacted clay till liner at brine ponds, is the adverse operating conditions. If suitable protective measures are followed to prevent general degradation of the liner due to adverse environmental conditions, then the additional factor of increased permeability due to

clay - brine interaction might be accommodated in a proper design. Compacted clay till liners could be a cost-effective alternative to lining with flexible polymeric membranes at large pond sites where suitable clay fill materials are available and the proper liner protection measures are followed.

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8. APPENDICES

8.1 A REVIEW OF CLAY PROPERTIES

8.1.1 Introduction

A number of factors influence the behaviour of clay soil and, in particular, its performance when used as a liner in contact with brine solutions. Fundamental factors affecting the performance of a liner comprised of natural materials are as follows:

a) clay content
b) clay mineralogy
c) cation exchange capacity (CEC)
d) soil permeability
e) pore water chemistry

The combination of physiochemical properties for a particular soil will determine its permeability characteristics. The fundamental physiochemical properties of clay minerals and their influence on the behaviour of compacted materials are discussed in the following section.

8.1.2 Clay Mineral Content

The percentage of clay minerals present in the soil is a major factor controlling the material's volume change behaviour, and hence its permeability. A clay mineral is defined as a crystalline material that exhibits plasticity because of its inherent ability to retain water. The composition of clay minerals is discussed in Section 8.1.3.

8.1.3 Clay Mineralogy

Clay minerals consist of hydrated aluminum silicate in a crystalline form. There are three general groups of clay minerals, all of which have similar engineering properties.

Clay minerals are formed from two basic structures - a silica and an aluminum octahedron. These basic units combine to form sheet structures. The various clay minerals are formed by stacking combinations of the basic sheet structures with different forms of bonding between the combined sheets (Yong and Warkentin 1975). Kaolinite, illite, and smectite (mortmorillonite) are the three principal clay minerals. Other clay minerals include chlorite, vermiculite, allophane, and attapulgite. A clayey soil usually contains a mixture of clay minerals, amorphous silicon, aluminum oxide, and iron.

8.1.3.1 Kaolinite. Kaolinite consists of repeating two-layered sheets. Each sheet consists of a silica tetrahedron sheet and an alumina octahedron sheet separated by a layer of oxygen atoms. The combined silica-alumina sheets are held together by hydrogen bonds. A typical kaolinite particle may consist of over 100 stacks.

8.1.3.2 Illite. The basic unit of illite is a three-layer system, which consists of a layer of alumina octahedra contained between two sheets of silica tetrahedra. The combined sheets are weakly bonded together by non-exchangeable potassium ions.

8.1.3.3 Smectite. Smectite has a structure similar to that of illite. However, the space between the combined sheets is occupied by water molecules and exhangeable cations instead of potassium ions. The bonds are weaker than for illite, with the result that smectite can swell much more in the presence of water. Clay tills in Alberta generally have a relatively high percentage of montmorillonite (Komex 1983).

Clay minerals may be identified by techniques of scanning electromicroscopy, X-ray diffraction, differential thermal analysis, and infrared spectroscopy. Basic properties of the three types of main clay minerals are shown in Table 19.

8.1.4 Cation Exchange

The surfaces of clay minerals are negatively charged. As a result, cations such as Na^+, Ca^{2+}, K^+, and Mg^{2+} present in the water in the void space are attracted to the clay

Table 19. Basic characteristics of common clay minerals.[a]

Mineral (1)	Supplier Source Trade Name (2)	Liquid Limit in % (3)	Plastic Limit in % (4)	Specific Gravity (5)	Surface Area in m^2/gm (6)	Cation Exchange Capacity Per 100 gm (7)	Fraction Finer Than 0.002 mm (8)	Estimated Ratio of Diameter to Thickness (9)
Kaolinite	Minerals and Chemicals Philipp Corp. Klondyke clay, McIntyre, Georgia	40 to 50	27 to 31	2.65	14	2.2	47	2 to 5
Illite	J.I. Eades Dept. of Geology Univ. of Illinois, Marblehead, Wisconsin	83 to 104	31 to 32	2.80		28	100	10 to 50
Smectite	American Colloid Company, Wyoming Volclay	190 to 1160	31 to 47	2.65 to 2.80	500 to 700	100	97	150 to 500

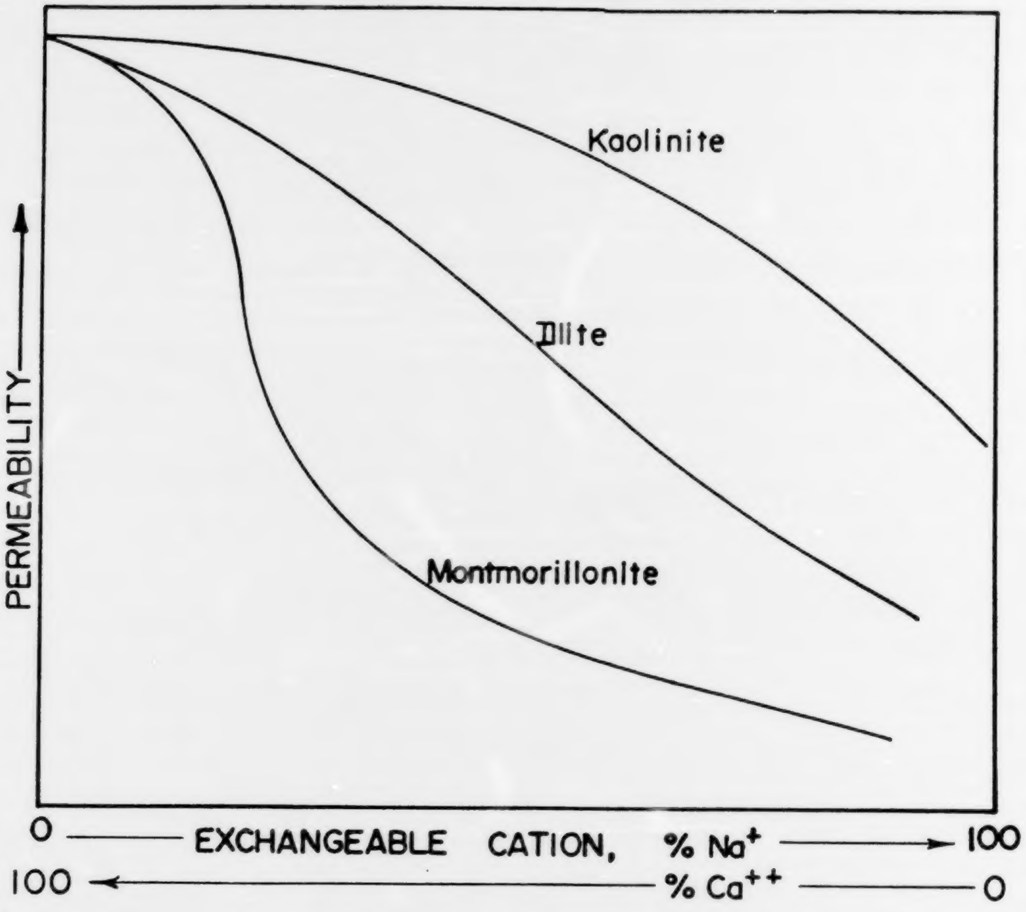
---

[a] Source: Mesri and Olson (1971).

particles in order to balance the negative charge and keep the whole unit electrically neutral. These cations are not held strongly to the particles and they may be replaced or exchanged by other cations. Cation exchange refers to the process whereby attracted (adsorbed) cations are replaced by other cations.

The concentration and valence of cations in the adsorbed water region of the clay minerals affect the clay mineral structure during sedimentation by either increasing or decreasing the net electrical repulsive force between sheet faces. Both increased cation concentrations and increased cation valence cause a decrease in net repulsive forces and thus a tendency for flocculation of clay particles. Conversely, either decreased cation concentrations or lower cation valences causes an increase in net repulsive forces and a tendency for the clay particles to disperse. Flocculated clays tend to have a more open, card-house structure and thus a higher hydraulic conductivity than dispersed clays. The effects of replacing monovalent Na^+ cations with divalent Ca^{2+} cations in montmorillonite, illite, and kaolinite are shown in Figure 30. Increasing the Ca^{2+} concentration results in more flocculated structures, which tend to be relatively open and porous, and hence exhibit higher permeability. By contrast, sodium-saturated clays tend to be dispersed, resulting in lower permeability. Smectite has a greater surface area available for cation exchange (termed cation exchange capacity) and thus is more affected by changes in cation type than either illite or kaolinite.

Cation concentrations in Alberta tills are relatively high (Pawluk and Bayrock 1969), resulting in flocculated structures (in situ). The state of flocculation in clay minerals has been experimentally related to the sodium absorption ratio (SAR) of the pore fluid and the total cation concentration of the pore fluid (Aitchison and Wood 1965). Relationships for smectite and illite are shown in Figure 31, together with values for Alberta tills as reported by Pawluk and Bayrock (1969). Points to the right of the appropriate clay mineral envelope indicate flocculated structures, while points to the left of the curve indicate dispersed structures.



(b)

Figure 30. Hydraulic conductivity of clay minerals. (From Yong and Warkentin, 1975)

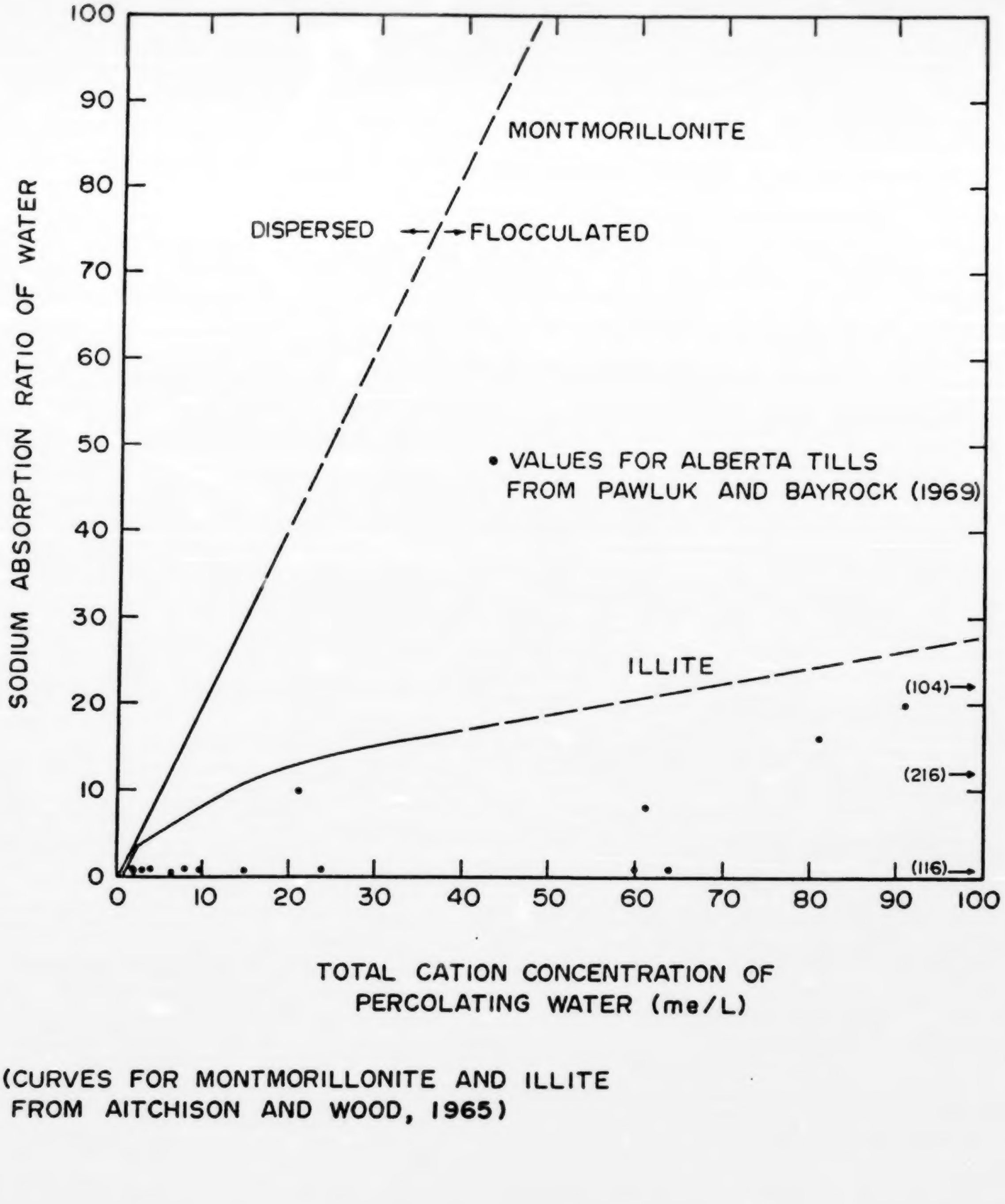


Figure 31. Flocculation of montmorillonite and illite as a function of SAR.

The data shown in Figure 31 suggest that most Alberta tills are in a flocculated state in situ.

8.1.5 Influence of Clay

As a general statement, the greater the quantity of clay minerals in the soil, the greater the potential for shrinkage or swelling, the lower the permeability, and the higher the plasticity. Since water is strongly attracted to the surface of clay minerals, it can be assumed as a first approximation that the majority of the water in the soil is associated with the clayey phase (Seed, Woodward, and Lundgren 1962). Using this approximation, one can estimate the amount of clay required to fill the voids of the granular phase and prevent direct contact between granular particles for any water content (Mitchell 1976). Following this approximation, the relationship of void ratio of the granular fraction to overall moisture content and the clay fraction required to fill the voids is presented in Figure 32. This figure illustrates that for moisture contents typical of compacted clay till, in the range of 10% to 20%, a relatively small amount of clay is required such that clay dominates the behaviour of the material.

The plasticity characteristics of various clay minerals in distilled water and the particle size ranges listed in tables 20 and 21 give an indication of the clay - water interaction. These characteristics also relate to the volume change properties, which follow the same pattern as the plasticity, i.e., the more plastic the material, the greater the potential swell and/or shrinkage.

The variation in permeability of single clay mineral mixtures to various solutions illustrates the important influence of the electrolyte concentration of the permeant and its interaction with the surface of clay minerals. For example, the permeability of smectite, illite, and kaolinite at various void ratios, when permeated with fresh water (a polar fluid with a high dielectric constant), are illustrated in Figure 33. The smectite (typically montmorillonite) has the lowest permeability for a given void ratio, as expected, reflecting the plasticity characteristics of this

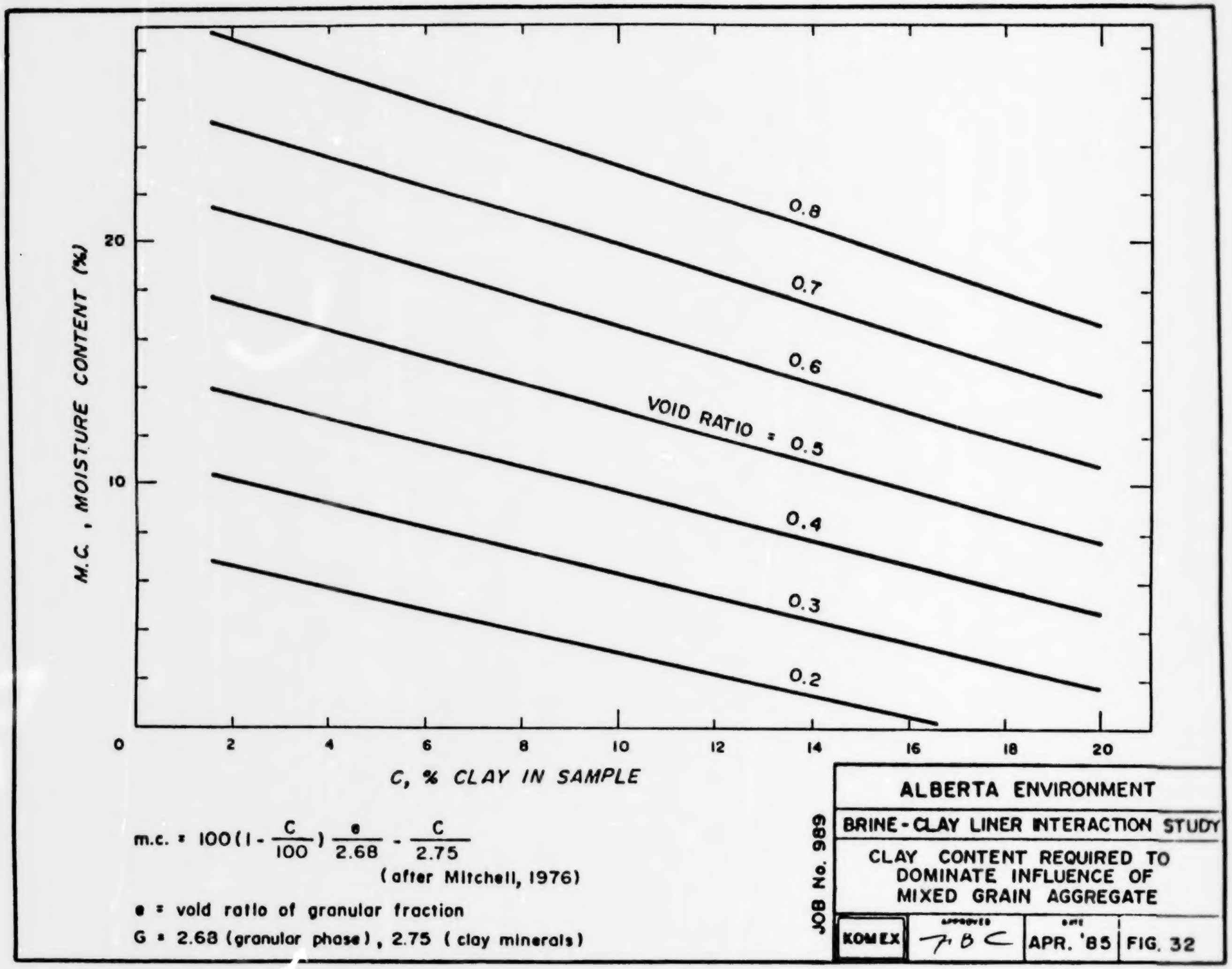


Figure 32. Clay content required to dominate influence of mixed grain aggregate.

Table 20. Atterberg limit values for the clay minerals.[a]

Mineral	Liquid Limit (%)	Plastic Limit (%)	Shrinkage Limit (%)
Montmorillonite	100 to 900	50 to 100	8.5 to 15
Nontronite	37 to 72	19 to 27	
Illite	60 to 120	35 to 60	15 to 17
Kaolinite	30 to 110	25 to 40	25 to 29
Hydrated Halloysite	50 to 70	47 to 60	
Dehydrated Halloysite	35 to 55	30 to 45	
Attapulgite	160 to 230	100 to 120	
Chlorite	44 to 47	36 to 40	
Allophane	200 to 250	130 to 140	

[a] Source: Mitchell (1976).

Table 21. Mineral composition of different particle size ranges in soils.[a]

Particle Size (micron)	Predominating Constituents	Common Constituents	Rare Constituents
0.1	Montmorillonite Beidellite	Mica intermediates	Illite (traces)
0.1 to 0.2	Mica intermediates	Kaolinite Montmorillonite	Illite Quartz (traces)
0.2 to 2.0	Kaolinite	Illite Mica intermediates Micas Halloysite	Quartz Montmorillonite Feldspar
2.0 to 11.0	Micas Illites Feldspars	Quartz Kaolinite	Halloysite (traces) Montmorillonite (traces)

[a] Source: Mitchell (1976).

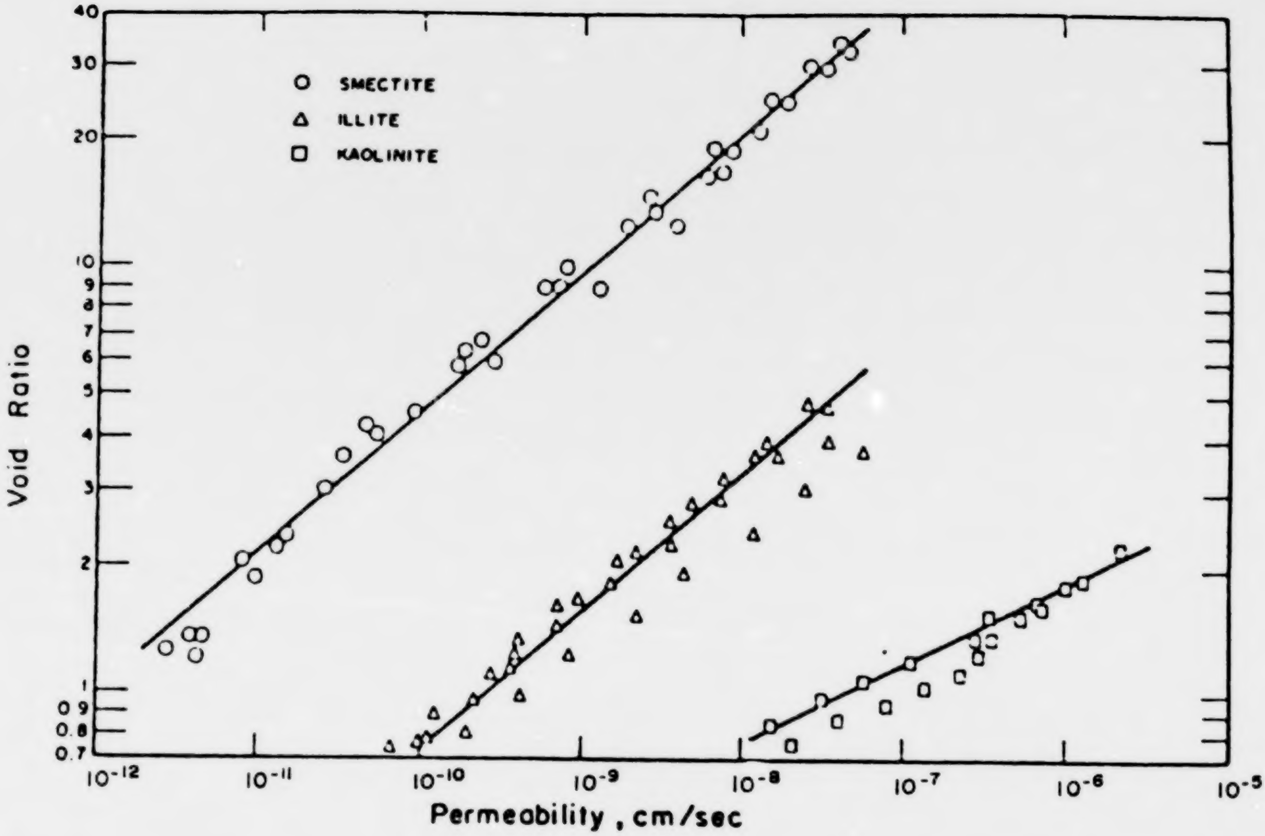


Figure 33. Coefficient of permeability of three sodium clays in water (from Mesri and Olson, 1971).

clay and the dominating influence of the bound water. When the fluid is non-polar (e.g., carbontetrachloride or benzene), all three clays have a similar void ratio - permeability relationship as illustrated in Figure 34. The results of these studies reported by Mesri and Olson (1971) indicate that the interaction between the permeant and clay minerals can have an important influence on permeability. If the interaction of the permeant and clay minerals is not a factor, the permeability is controlled by the grain arrangement and flow channels only.

8.2 DESCRIPTION OF PROCOR BRINE POND AND SAMPLES COLLECTED FOR LABORATORY TESTING

8.2.1 Background on Clay Liner Investigated

The Procor Limited LPG storage facility is located about 14 km northeast of Fort Saskatchewan and 12 km south of Redwater, Alberta in LSD 9 and 10, SEC 1, TWP 56, RGE 22 W4M. The site is about 1 km west of the North Saskatchewan River. A key plan is presented as Figure 35.

The plant was constructed in 1976, and a brine pond, consisting of two cells, was constructed during the summer of 1978. The pond began operation in October 1978 and was used until mid-1983. A layout of the site is shown in Figure 36. Some time after construction of the ponds, high chloride concentrations were measured in groundwater monitor wells, indicating relatively high seepage rates through the clay liners. The first significant concentration of sodium chloride, approximately 300 mg/L in Well No. 7, was measured in September 1980 as shown in Figure 37. As a result of the unsatisfactory performance of the pond, it was decided to rehabilitate the pond and to install a polymeric membrane liner. This work was done in 1983-84, and the rehabilitated pond was commissioned in July 1984. During the reconstruction, Komex had the opportunity to obtain block samples from the compacted clay till "liner" and the underlying native soil at the locations shown in

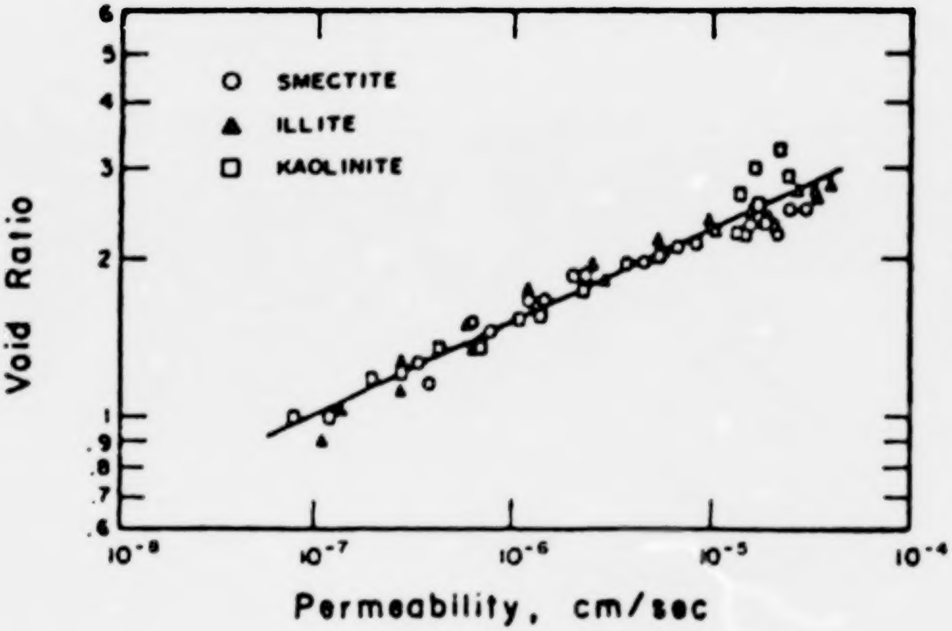
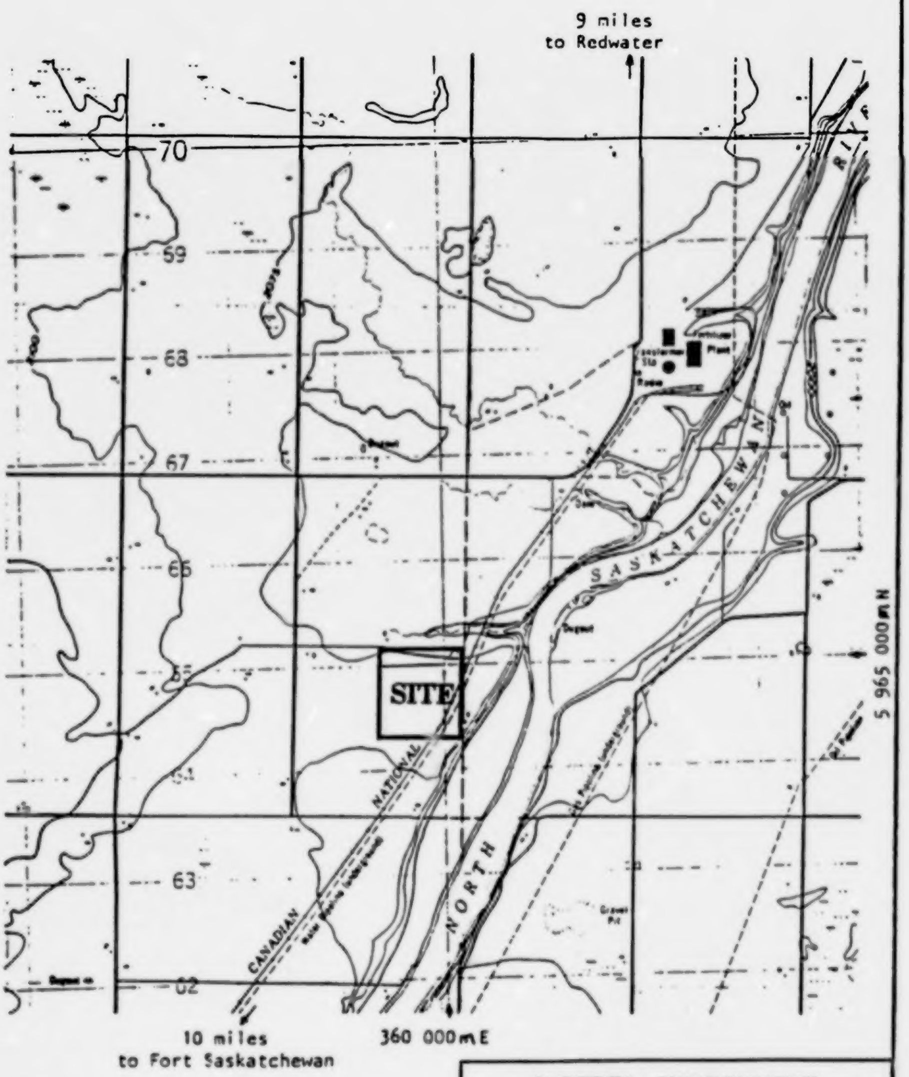


Figure 34. Coefficient of permeability of three clay minerals in nonpolar fluids (from Mesri and Olson, 1971).



SITE LOCATION :

LSD 9 AND 10, SECTION 1
Tp. 56, R. 22 W4M.

ALBERTA ENVIRONMENT
BRINE-CLAY LINER INTERACTION STUDY
SITE LOCATION PLAN
PROCOR BRINE POND

KOMEX | APPROVED | DATE APRIL '85 | FIG. 35

Figure 35. Site location plan, Procor brine pond.

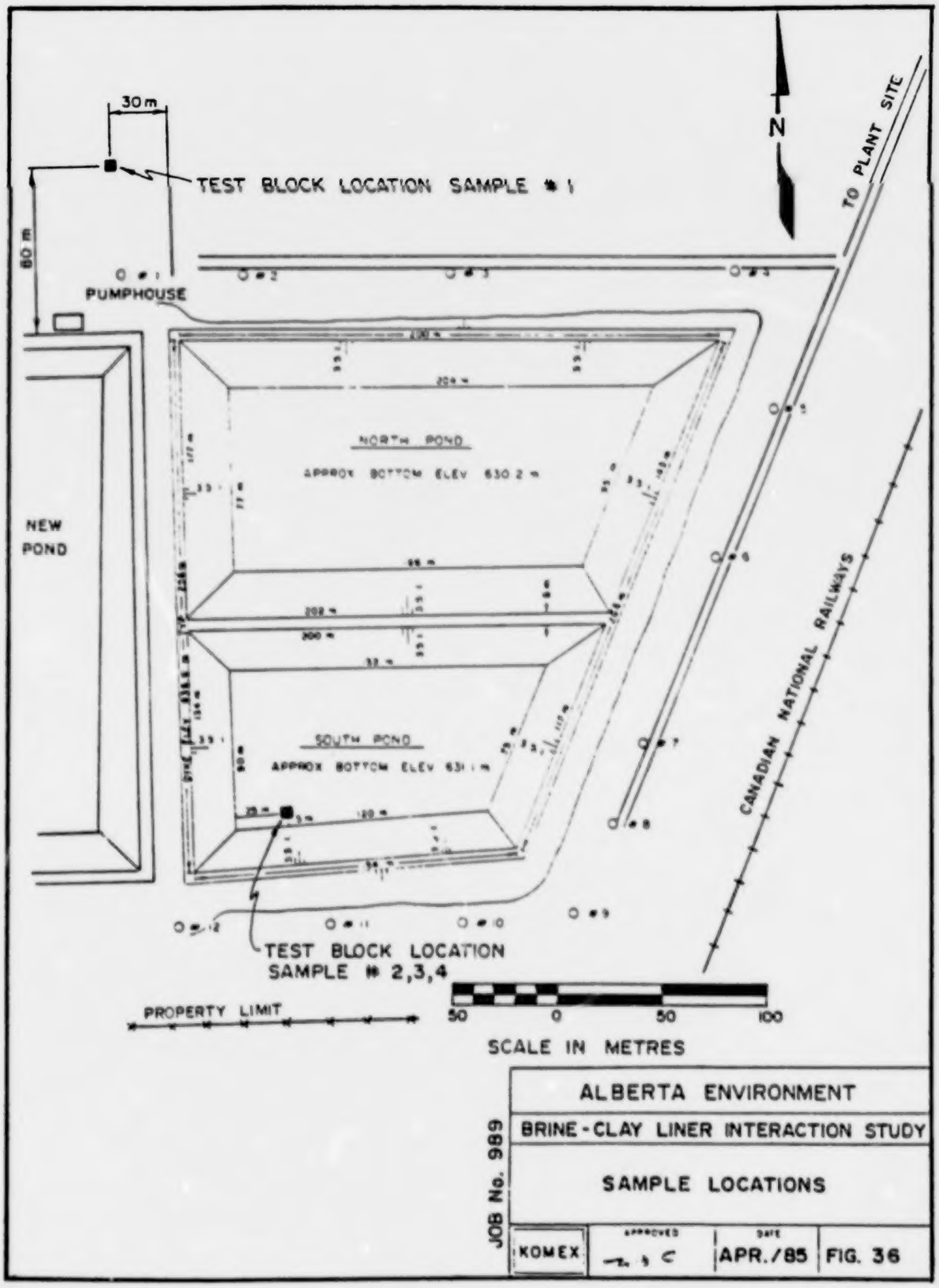
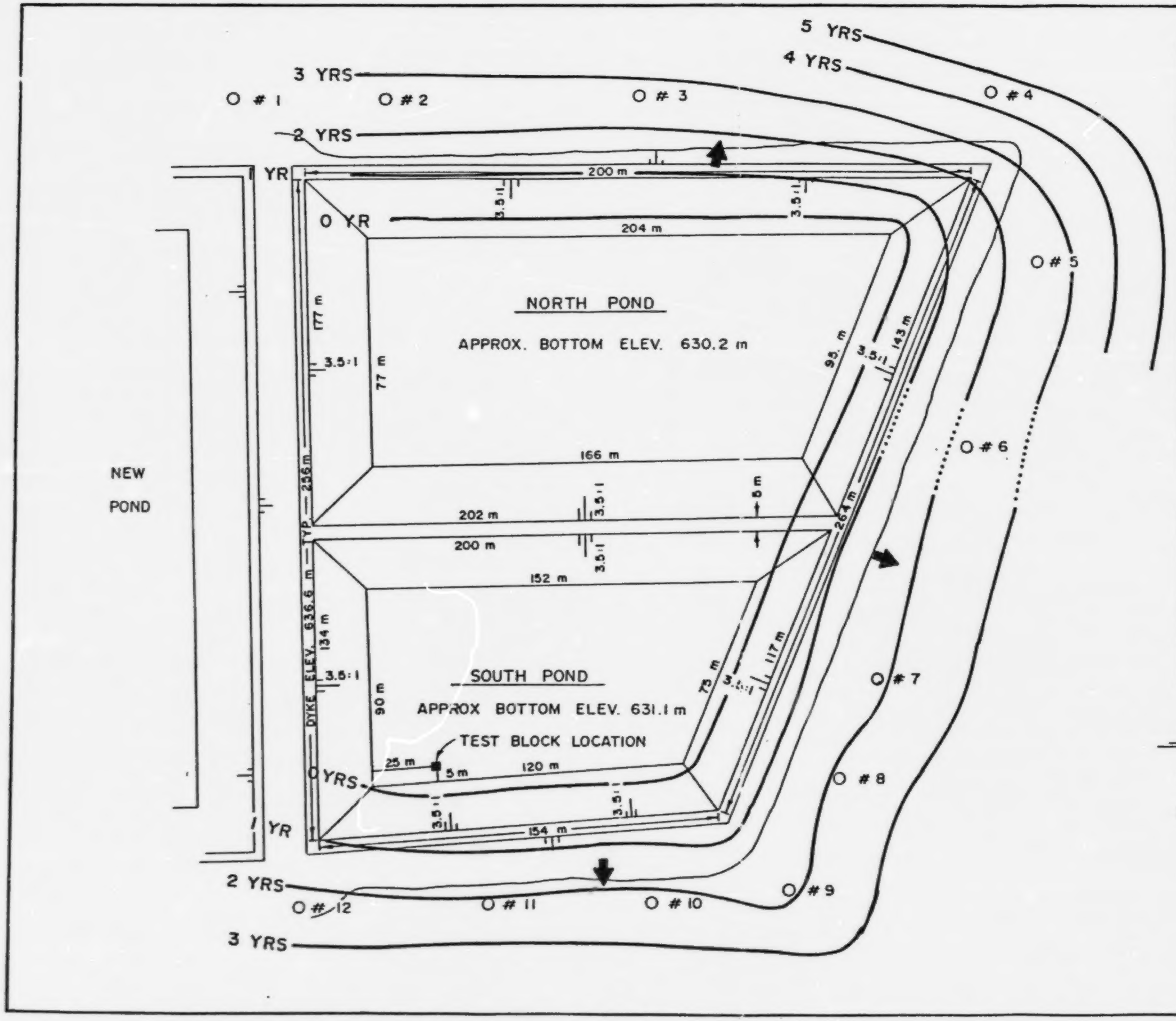


Figure 36. Sample locations.



OBSERVED DATA				
WELL No.	FIRST OBSERVATION		PEAK OBSERVATION	
	TIME (YRS)	$[Cl^-]$ (mg/L)	TIME (YRS)	$[Cl^-]$ (mg/L)
2	2.4	300	3.8	500
3	2.5	450	5.2	22 000
4	4.6	60	5.3	400
5	2.4	700	2.4	700
6	N/A	—	—	—
7	1.9	300	5.3	78 000
8	2.1	620	4.8	75 000
9	1.9	4 000	2.3	10 000
10	2.4	190	4.4	350
11	N/A	—	—	—
12	2.4	220	4.7	1500

LEGEND	
—5—	TIME IN YEARS FOR SIGNIFICANT Cl^- INCREASE
➡	BRINE PLUME FRONT ADVANCEMENT
○ No. 6	MONITOR WELL 6

NOTES:

1. CONTOURS ARE APPROXIMATE ONLY.
2. CHLORIDE CONCENTRATION IN TABLE ARE APPROXIMATE ONLY.

ALBERTA ENVIRONMENT
BRINE-CLAY LINER INTERACTION STUDY
BRINE PLUME ADVANCEMENT
JOB No. 989
KOMEX
APPROVED 7BC
DATE APR./85
FIG. 37

Figure 37. Brine plume advancement.

Figure 36. This section described conditions in the pond bottom and classification tests performed on the clayey till liner materials.

8.2.2 Brine Pond Operation

Natural gas liquid (NGL) is stored in underground caverns formed by solution cavities in natural salt deposits. The NGL is displaced by brine solution, which is temporarily stored on the surface in a pond. When the NGL is withdrawn from the caverns, the brine is pumped from the pond back into the caverns to displace the gases. The peak demand for gas products begins in the fall and ends in the spring. Consequently, the level of stored brine is gradually lowered throughout the winter to an ideally empty condition by spring.

Although deviations from the usual operations occur, it can be reasonably expected that pond liner will be subjected to variations in hydrostatic head, temperature, and alternating wetting and drying cycles. Additionally, due to the high concentrations of the brine and associated depressed freezing temperatures of -10°C or lower, it is conceivable that the reservoirs are also subjected to detrimental freeze-thaw cycles, as opposed to normal water retention ponds where an ice cover generally prevents subgrade freezing. The interior pond slopes are exposed to alternating concentrated brine and fresh water, such as from snowmelt, resulting in possible adverse physiochemical alteration of the subgrade soil.

The above operating conditions and expected effects can be detrimental to the integrity of a clay lined reservoir and can lead to high brine seepage rates.

8.2.3 Site Conditions

8.2.3.1 Topography. The ground in the region is slightly undulating, rising to the west and sloping east toward the river valley. The valley wall drops off abruptly about 23 m to a narrow river terrace. The river elevation is about 594 m at this location.

The pond site is nearly level. The crest of the dykes averages approximately 636.6 m elevation[1]. The pond bottom is at an elevation of approximately 630.6 m, representing a potential maximum storage depth of 6.0 m.

8.2.3.2 Regional geology. The bedrock geology in the area consists of Upper Cretaceous marine sandstone, siltstone, and shale. Uplift and erosion during the Tertiary period resulted in the formation of bedrock valleys. The Beverly channel, which generally underlies the present North Saskatchewan River Valley, is a major depression in the bedrock and contains alluvial Fort Saskatchewan sands and gravels. The Beverly channel is located somewhat to the east of the site.

Glaciation during the Quaternary period likely resulted in further modifications to the bedrock profile. The last Wisconsin glaciation, about 20,000 years ago, deposited a layer of ground moraine, or till, in the site area. During retreat of the ice sheets, a proglacial lake formed in front of the retreating ice, called Lake Edmonton. The Fort Saskatchewan-Redwater area was near the eastern shore of the lake, and thus the lake deposits in the area are relatively thin and comprise silts, sands, and clays.

8.2.3.3 Subsurface conditions

8.2.3.3.1 General. The subsurface data discussed herein are based on reports by Hardy Associates (1976), Clifton Associates (1981), and fieldwork carried out by Komex (1981, 1984). The following discussion presents a simplified interpretation of subsurface conditions encountered at the pond site; detailed information on conditions encountered at borehole locations is presented on the test hole logs in Komex (1981, 1984), for example.

---

[1] Elevations are reference to mean sea level.

8.2.3.3.2 Bedrock. Bedrock is encountered across the Procor site at elevations ranging from approximately 630 m on the west side of the site to 609 m near the southeast corner. Beneath the pond, bedrock is estimated to be close to or below elevation 620 m, representing a minimum overburden thickness below the pond bottom of roughly 10 m.

8.2.3.3.3 Soil overburden. The original ground at the pond site consisted of a layer of topsoil 0.6 m thick overlying up to 2 m of glaciolacustrine silt and clay sediments. It is understood that this material was used to construct the clay liner. The glaciolacustrine deposit consists primarily of silt, with about 20% by weight of clay sized particles.

The glaciolacustrine sediments overlie a relatively thick deposit of silty clay till material. The till is of medium plasticity, with traces to a little sand and gravel, and frequent coal fragments. The material is generally oxidized and slightly desiccated throughout, indicating that the original, long-term water table was quite low prior to construction of the pond. Natural water contents range from about 12% to 20% and are typically about 15%. Thus, the soil is near the plastic limit, indicating a high degree of overconsolidation and/or weathering. Standard Penetration Test N-values vary from about 15 to 25, indicating that the till is of very stiff consistency with unconfined compressive strengths of up to 350 kPa.

The silty clay till contains frequent fine silt partings in both horizontal and vertical orientations, likely due to the effects of overconsolidation and weathering, and contains occasional silt and sand lenses.

A basal sand layer was also encountered directly over bedrock in three of the four holes drilled to bedrock. The sand gradation is fine to medium with a little silt, and may be relatively extensive or confined to bedrock lows.

8.2.3.3.4 Groundwater. Groundwater levels reported by Hardy Associates (1976) prior to construction of the existing ponds indicated that the overburden was relatively unsaturated, with local perched water in sand and silt seams. This conclusion is supported by the regional hydrogeological map prepared by the Alberta Research Council (ARC), which indicates a piezometric elevation of about 610 m for groundwater in the bedrock below the site. The ARC hydrogeological map also indicates strong downward gradients in the upper layers and flows that are southeasterly toward the river. The basal sand layer, if continuous, may represent a perched groundwater flow along the bedrock surfaces. The piezometric levels in this layer do not appear to be artesian.

In general, the high elevations of the site, with respect to the nearby river, suggests that groundwater levels due to infiltration of precipitation and runoff should be well below the pond bases. It is understood that no significant seepage was encountered during construction of the existing ponds.

Local groundwater mounding has occurred, however, due to seepage of brine from the old claylined pond. Piezometer installations by Clifton Associates (1981) around the ponds showed that saturated conditions existed immediately adjacent to the ponds. Piezometer readings indicate downward gradients of about 0.2 to 0.3.

The groundwater elevations recorded in the piezometers, and the surface observations made by Komex on June 30, 1981, generally indicated the existence of a groundwater table mound due to brine seepage, with varying degrees of lateral spread and downward gradient on the four sides of the existing ponds. On the south side, the groundwater mound is below ground surface at all points, with primarily horizontal flow and small downward gradients. Piezometric conditions on the east side are similar near the dyke, but the lateral extent of the mound is less. Thus, most of the seepage is eventually in a downward direction. No surface seepage was observed along the toe of the north dyke. Piezometer readings indicated high groundwater levels near the dyke, but essentially little lateral spreading and strong downward gradients. An excavation for a wellhead along the north side of the ponds was experiencing considerable seepage in 1984 from a zone below a depth of about 1 m. The seepage was being controlled by a small pump. According to contractors on-site, seepage was not encountered at other locations on the property.

8.2.4 Sampling

Block and disturbed samples were obtained for the study from the original pond bottom and in a location well removed from the pond, as described below.

8.2.4.1 Description of Block Samples.

1. Uncontaminated Sample (Sample #1): A sample of "uncontaminated" clay was taken approximately 90 m from the north side of the new brine pond (see Figure 36) in April 1985. The sample was taken from a depth of 2.0 m at an elevation of approximately 635.2 m. The till sample was very dense, with a low moisture content (6% to 8%).
2. Contaminated Samples (Samples #2, #3, and #4): Block samples of contaminated clay till were taken from three levels in a test pit excavated in the pond bottom in November 1984 at the location shown in Figure 36. A sketch showing the positions of the samples in elevation with respect to the top and bottom of the clay liner is presented in Figure 38. Samples were taken at depths below the pond bottom of 0 m to 0.20 m, 0.20 m to 0.40 m, and 0.46 m to 0.68 m. The samples were less dense and more moist than the uncontaminated material, with moisture contents ranging from about 18% to 40%. Photographs of selected sample sections accompanied with detailed soil descriptions are presented as Plates 1, 3 and 3. The geotechnical properties of this material are discussed in the text of the report. There is some

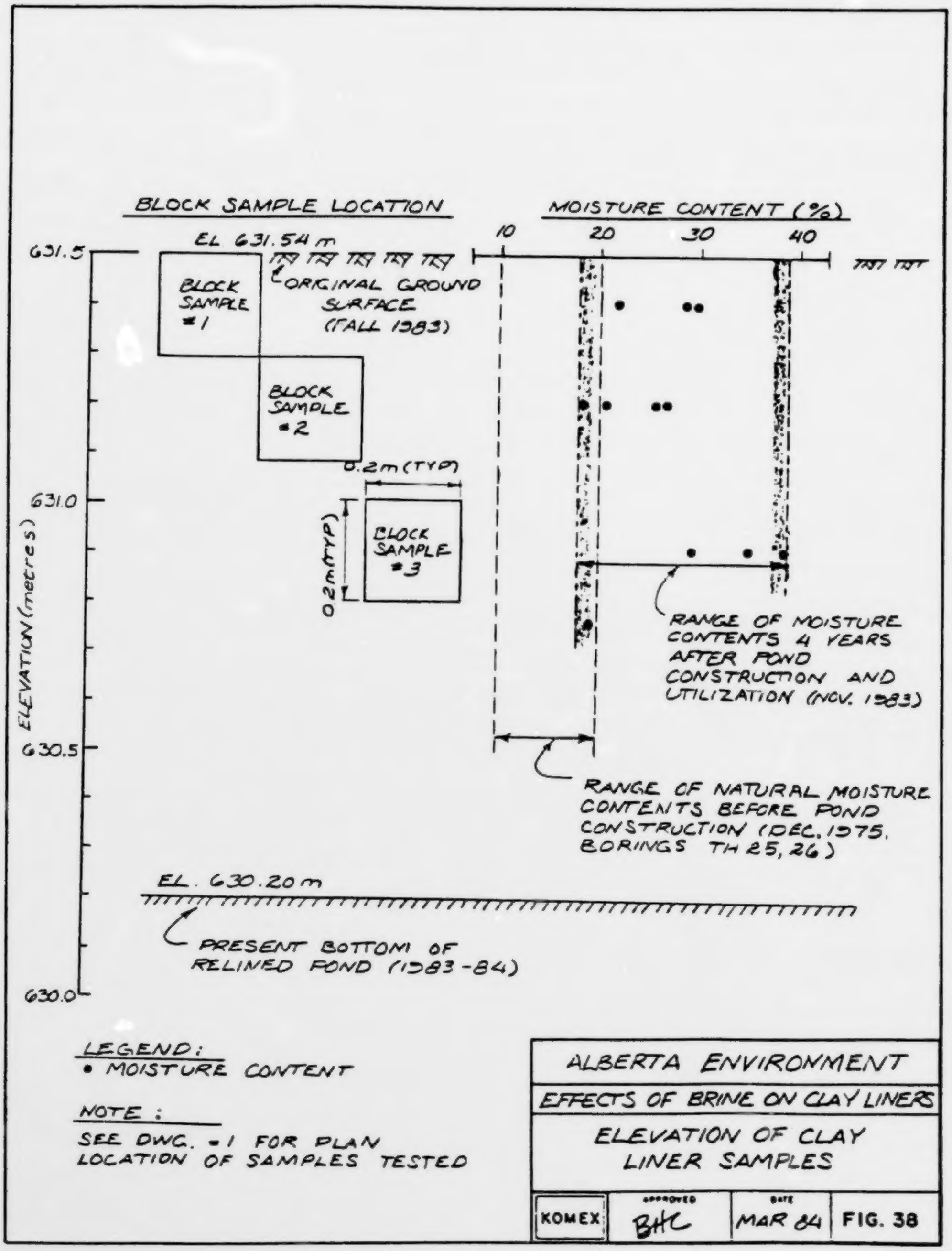

BLOCK SAMPLE LOCATION
MOISTURE CONTENT (%)
10
20
30
40
631.5
EL 631.54 m
BLOCK SAMPLE #1
ORIGINAL GROUND SURFACE (FALL 1983)
BLOCK SAMPLE #2
0.2m (TYP)
631.0
0.2m (TYP)
BLOCK SAMPLE #3
ELEVATION (metres)
RANGE OF MOISTURE CONTENTS 4 YEARS AFTER POND CONSTRUCTION AND UTILIZATION (NOV. 1983)
630.5
RANGE OF NATURAL MOISTURE CONTENTS BEFORE POND CONSTRUCTION (DEC. 1975, BORINGS TH 25, 26)
EL. 630.20 m
PRESENT BOTTOM OF RELINED POND (1983-84)
630.0
LEGEND:
• MOISTURE CONTENT
NOTE:
SEE DWG. #1 FOR PLAN LOCATION OF SAMPLES TESTED
ALBERTA ENVIRONMENT
EFFECTS OF BRINE ON CLAY LINERS
ELEVATION OF CLAY LINER SAMPLES
KOMEX
APPROVED
BHC
DATE
MAR 84
FIG. 38

Figure 38. Elevation of clay liner samples.

PLATE 1; SA#2: Contaminated liner sample. Olive-brown CLAY TILL, silt, little sand, occasional subangular pebbles of max. 3 mm Ø, trace fine roots, mottled, trace iron staining, firm to stiff, slight blocky structure, low plasticity, moist, top 5 cm of sample very moist.

PLATE 2; SA#3: Contaminated liner sample. Olive-brown, CLAY TILL, silt, trace sand, occasional subangular to rounded pebbles of max. 15 mm Ø, one sandstone cobbles of 38 mm Ø, trace fine roots, stiff, fractured structure, low plasticity, moist; lower layer of sample (indicated) grey-black CLAYEY SILT, stiff, organic odour, damp to moist.

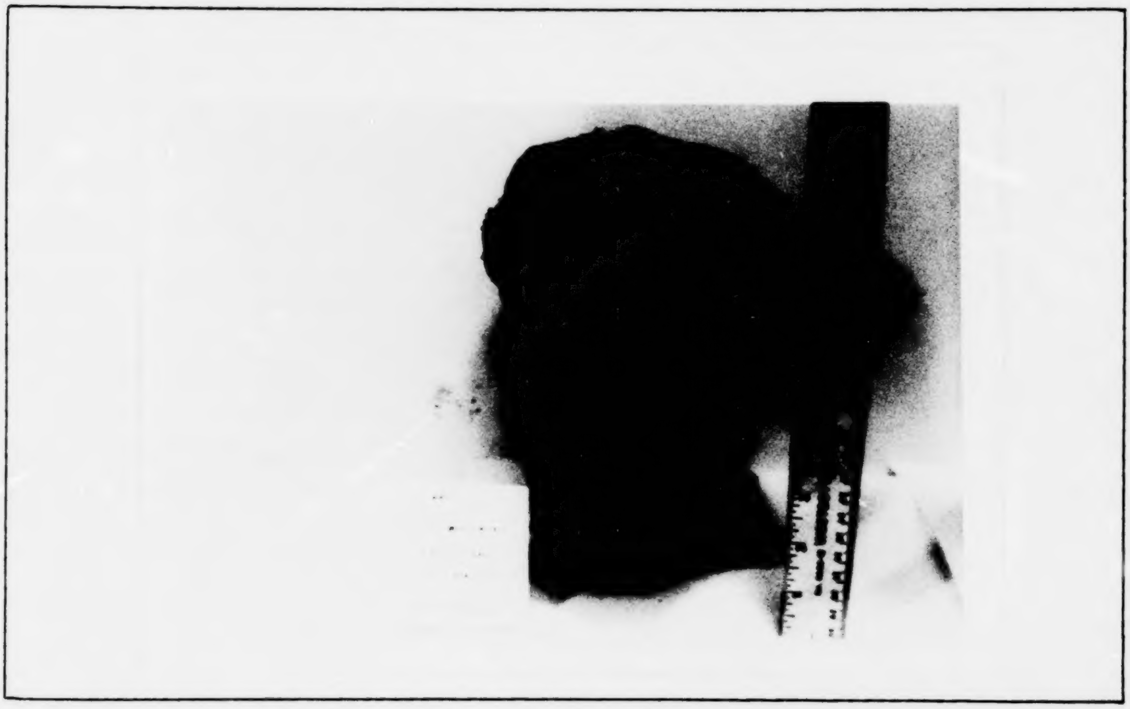


PLATE 3; SA#4: Contaminated liner sample. Upper unit (liner) - grey-brown CLAY TILL, mottled, some silt, trace sand, occasional subangular pebbles of max. 10 mm Ø, trace roots, stiff, low to medium plasticity, moist. Lower unit (subsoil) - grey-black SILTY CLAY, trace to little sand, calcite stringers, organic odour, very stiff, defined blocky structure, less disturbed than upper unit, low plasticity, damp to moist.

variation in the sample gradations, with the percentage of silt and clay sizes ranging from 10% to 40%, particularly in SA#4, where a separation between the liner and underlying subsoil is observed. All of the contaminated samples are as fine as, or finer than, the sample of uncontaminated clay.

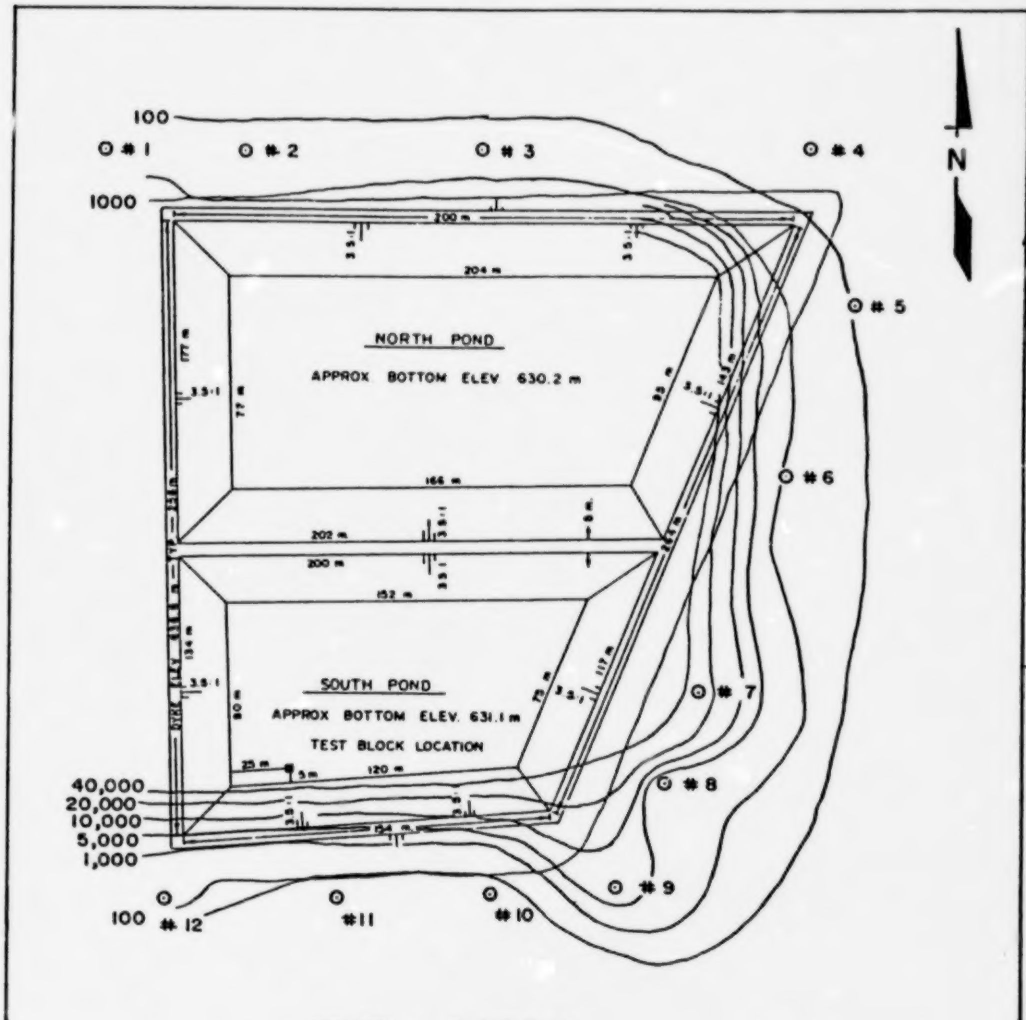
8.2.5 Monitoring and Pond Performance

A number of groundwater monitoring wells were installed during the construction of the pond as indicated in Figure 36. The main purpose of these wells was to monitor the movement of chloride ion in the area around the pond. During the first two years after construction, chloride ion concentrations obtained in the monitoring wells were relatively low, except for one well that had consistently indicated high readings. In the winter of 1983, the chloride concentration in a number of wells began to increase significantly, indicating a relatively high seepage rate through the clay liner. In June 1981, a conductivity survey was conducted. The report suggested that large values of conductivity were recorded near the dykes, confirming brine intrusion. In the summer of 1982, the chloride concentration in two of the monitoring wells reached a level of 75000 mg/L (refer to contours of chloride concentration in Figure 39).

During the winter of 1983, the brine pond was upgraded. The separating dyke between the two cells of the pond was removed and the entire area of the pond was lined with a high density polyethylene (HDPE) membrane.

It was believed that the high field permeability was mainly due to shrinkage of the clay liner, which was caused by the high sodium concentration leading to changes in the adsorbed water around the clay minerals.

The monitoring data summarized in figures 37 and 39 can be used to evaluate the effective permeability of the compacted clay liner. The results of this analysis are summarized in Figure 40, which indicates that the most probable permeability of the



TIME = 3 YEARS
(OCT. 1981)

LEGEND

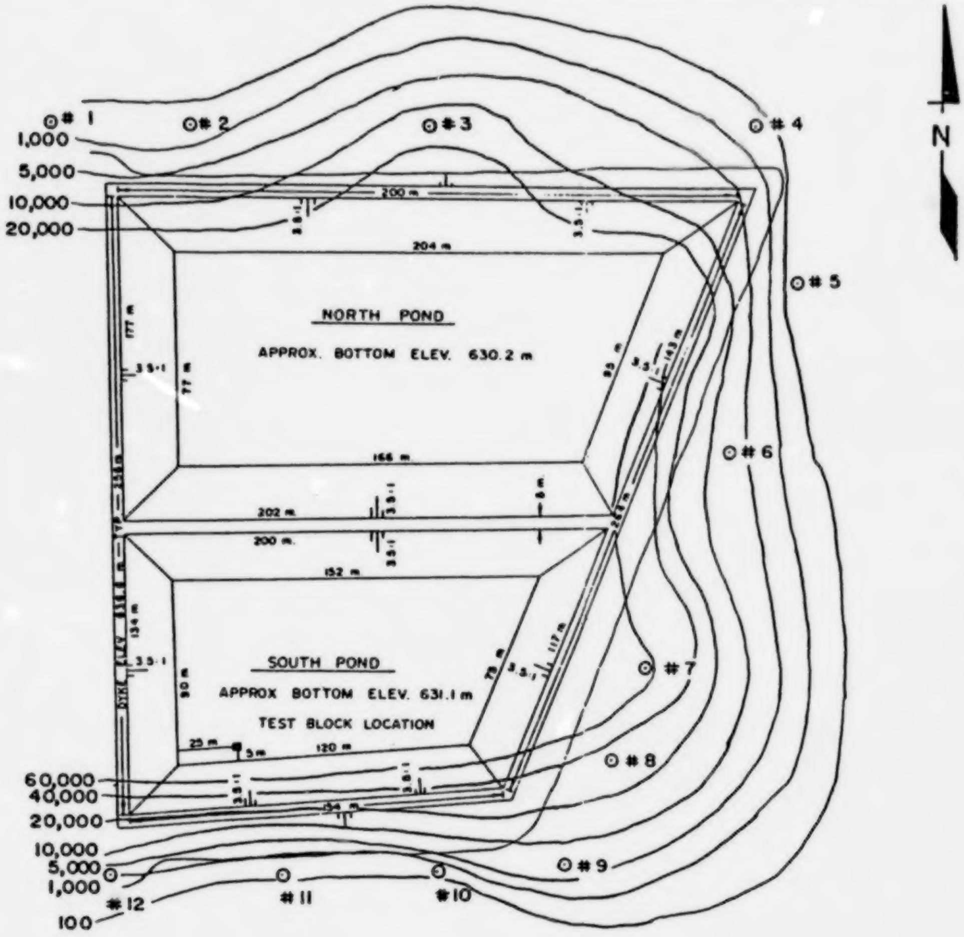
——— CHLORIDE CONCENTRATION CONTOUR (mg/l)

⊙#10 MONITOR WELL 10

AR

NOTE :

1. CONTOUR
ARE AP



TIME = 5 YEARS
(OCT. 1983)

APPROX. SCALE
(METRES) 50 0 50 100

OTE:

CONTOURS AND CHLORIDE CONCENTRATIONS
ARE APPROXIMATE ONLY.

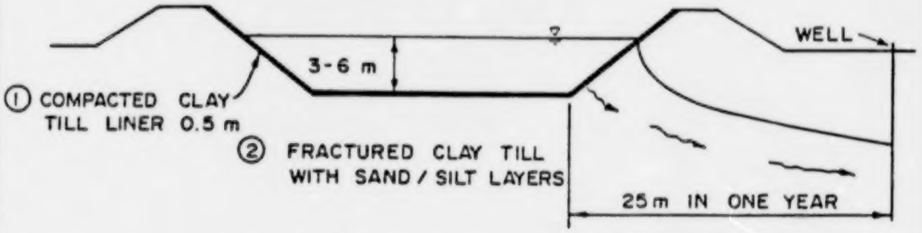
ALBERTA ENVIRONMENT

BRINE-CLAY LINER INTERACTION STUDY

BRINE PLUME MIGRATION

JOB No. 969

KOMEX	APPROVED	DATE APR. /85	FIG. 39


3-6 m
WELL
① COMPACTED CLAY TILL LINER 0.5 m
② FRACTURED CLAY TILL WITH SAND / SILT LAYERS
25 m IN ONE YEAR

KNOWN: $t_{\textcircled{1}} + t_{\textcircled{2}} = 1 \text{ year}$ $\quad t = \frac{d}{ki}$

SAY: $i_{\textcircled{1}} = \frac{3\text{m}}{0.5} = 6$ $\quad i_{\textcircled{2}} = 0.20$

$$\therefore \quad \frac{0.5}{k_{\textcircled{1}} \cdot 6} + \frac{25}{k_{\textcircled{2}} \cdot 0.2} = 1 \text{ year}$$

CASE 1: liner has no influence

$\therefore k_{\textcircled{1}} = k_{\textcircled{2}} = 2.5 \times 10^{-6}$ cm/sec

CASE 2: liner has same k as subsoil

$\therefore k_{\textcircled{1}} = k_{\textcircled{2}} = 2 \times 10^{-6}$ cm/sec

CASE 3: subsoil more pervious than liner (eg. sand/silt layering)

$\therefore$ $k_{\textcircled{2}}$ cm/sec x 10^{-3}	$k_{\textcircled{1}}$ cm/sec x 10^{-7}
10.0	5.5
1.0	8.7
0.8	10.0
0.1	N/A

ALBERTA ENVIRONMENT
BRINE-CLAY LINER INTERACTION STUDY
BACK ANALYSIS OF EFFECTIVE PERMEABILITY , PROCOR LINER SITE
JOB No. 989
KOMEX
APPROVED ス C
DATE APR. '85
FIG. 40

Figure 40. Back analysis of effective permeability, Procor liner site.

liner is in the range of 2 x 10^{-6} cm/sec. This estimate is not based on field measurements, but is surprisingly similar to "in situ" permeability estimates using Shelby tube samples of the liner as discussed previously.

8.3 DESCRIPTION OF LABORATORY TEST PROGRAM AND PROCEDURES

8.3.1 Testing Program

The testing program was conducted in three distinct phases, examining geotechnical characteristics, determining hydraulic properties, and evaluating microstructure information.

The uncontaminated and contaminated samples were first classified for gradation, moisture content, and plasticity characteristics. A compressibility test was performed on sample #2 to determine loading characteristics and initial hydraulic behaviour. Subsequently, compaction tests were carried out utilizing both tap water and brine as moulding liquids. For each combination of material and moulding water considered, hydraulic conductivity tests were performed on compacted samples with tap water and brine as permeants. In situ permeability tests were also carried out on samples #2 and #3 to simulate field conditions. Selected index tests were also conducted before and after hydraulic conductivity tests to determine net changes, if any.

Scanning electron microscope (SEM) and X-ray diffraction tests were performed on the soil samples to determine microstructure composition and the effect of brine on soil structure. Chemical analyses were conducted on the soil samples and brine permeant to determine chemical composition and main ion content.

A summary of the tests performed on the contaminated and uncontaminated samples is presented in Table 22.

8.3.2 Testing Procedure

To assess the performance of brine-saturated clay till material, the uncontaminated and contaminated liner samples obtained were subject to various geotechnical and hydraulic property tests.

Table 22. General summary of tests and number of tests performed.

		Geotechnical					Hydraulic Conductivity			Microstructure & Chemical (a)		
		Classification					Compacted Samples (b)		In Situ Samples			
							Permeant		Permeant			
Sample #	Added Moulding Liquid	Moisture Content (c)	Atterberg Limits	Gradational Character-istics	Consolidation	Compaction	Fresh	Brine	Brine	SEM (c)	X-Ray Dif-fraction	Chemical Analysis
1 (Uncontaminated)	Fresh	2	1	2		1	1	1		1	1	1
	Brine		1			1	1	1				
	Brine Soak(e)		7			1	1	1				
2 (Contaminated)	Fresh	10	1	2		1	1	1		1	1	1
	Brine		1		1	1		1	1			
3 (Contaminated)	Fresh	10	1	1								1
	Brine		1					1	1			
4 (Contaminated)	Fresh	10	1	3						1	1	1
	Brine		1									
BRINE LIQUID												1

[a] Analyses determined from in situ moulding waters of samples.
[b] SA#2 generally taken as representative of contaminated samples.
[c] Moisture contents determined from in situ moulding waters of samples.
[d] SEM - Scanning Electron Microscope.
[e] Brine Soak - material soaked in brine for 48 hr and air dried to appropriate M.C. Any moulding water added is brine.

Geotechnical characterization for individual samples was determined typically from the following standardized tests:

• Particle Size Analysis	ASTM D422[1]
• Atterberg Limits	ASTM D423, 424
• Moisture Content	ASTM D2216
• Sample Examination	ASTM D2487
• Moisture-Density Tests	ASTM D698
• Compressibility Tests	ASTM D2435

Hydraulic properties were determined from falling head tests performed on natural and artificially contaminated[2] samples. As no specific standard is applicable to falling head tests, procedures recommended by Olson and Daniel (1981) and Mitchell et al. (1965) were followed, where applicable. A typical hydraulic conductivity test for a compacted sample was conducted as follows:

1. Prepare and compact sample in cell as per ASTM D698 to approximately 2% wet-of-optimum moisture content.
2. Remove material from both sides of the cell until a 5 cm thick disc remains in the middle of the cell. Ensure exposed surfaces are rough and not moulded smooth.
3. Replace removed materials with filter cloth and coarse sand filter material.
4. Complete permeameter cell.
5. Connect standpipe and initiate readings.

An in situ hdyraulic conductivity test was conducted as follows:

1. Gently push a Shelby tube sampler into the soil block to obtain an "undisturbed" sample.
2. Remove material from bottom of sample to accommodate bottom plug.
3. Replace removed material and fill top of permeameter with coarse sand and filter cloth separators.

---

[1] ASTM - American Society for Testing and Materials

[2] The term "contaminated" is used to distinguish exposure to brine modelling fluids and/or permeants as opposed to the use of fresh water.

4. Install top plug.
5. Connect standpipe and initiate readings.

The computation of a hydraulic conductivity value between two discriminate time points is performed using the following relationship:

$$k = 2.3 \frac{a.L}{A(t_1 - t_0)} \log_{10} \frac{h_0}{h_1} \text{(e.g., Lambe and Whitman 1979)}$$

Where: k = hydraulic conductivity

L = the length of soil sample in the permeameter

A = the cross-sectional area of the permeameter

t_0 = the time when the water level in the standpipe is at h_0

h_0, h_1 = the heads between which the permeability is determined

a = cross-sectional area of the standpipe

t_1 = the time where the water level in the standpipe is at h_1

In addition to basic testing, scanning electron microscope (SEM), X-ray diffraction analysis, and chemical analysis were performed by independent laboratories. The results of these tests and procedures followed are contained in Sections 8.4 and 8.5.

8.3.3 Specialized Testing Apparatus

The hydraulic conductivity testing apparatus was manufactured locally to Komex specifications and falls into two categories: in situ permeameter and compacted permeameter, which are individually described below.

8.3.3.1 In Situ permeameter. The permeameter is essentially a 8 cm nominal diameter Shelby tube cut to an appropriate length and sealed with removable plugs at both ends, as shown in Figure 41. Galvanized fittings are attached to the plugs to accommodate standpipe and outlet attachments.

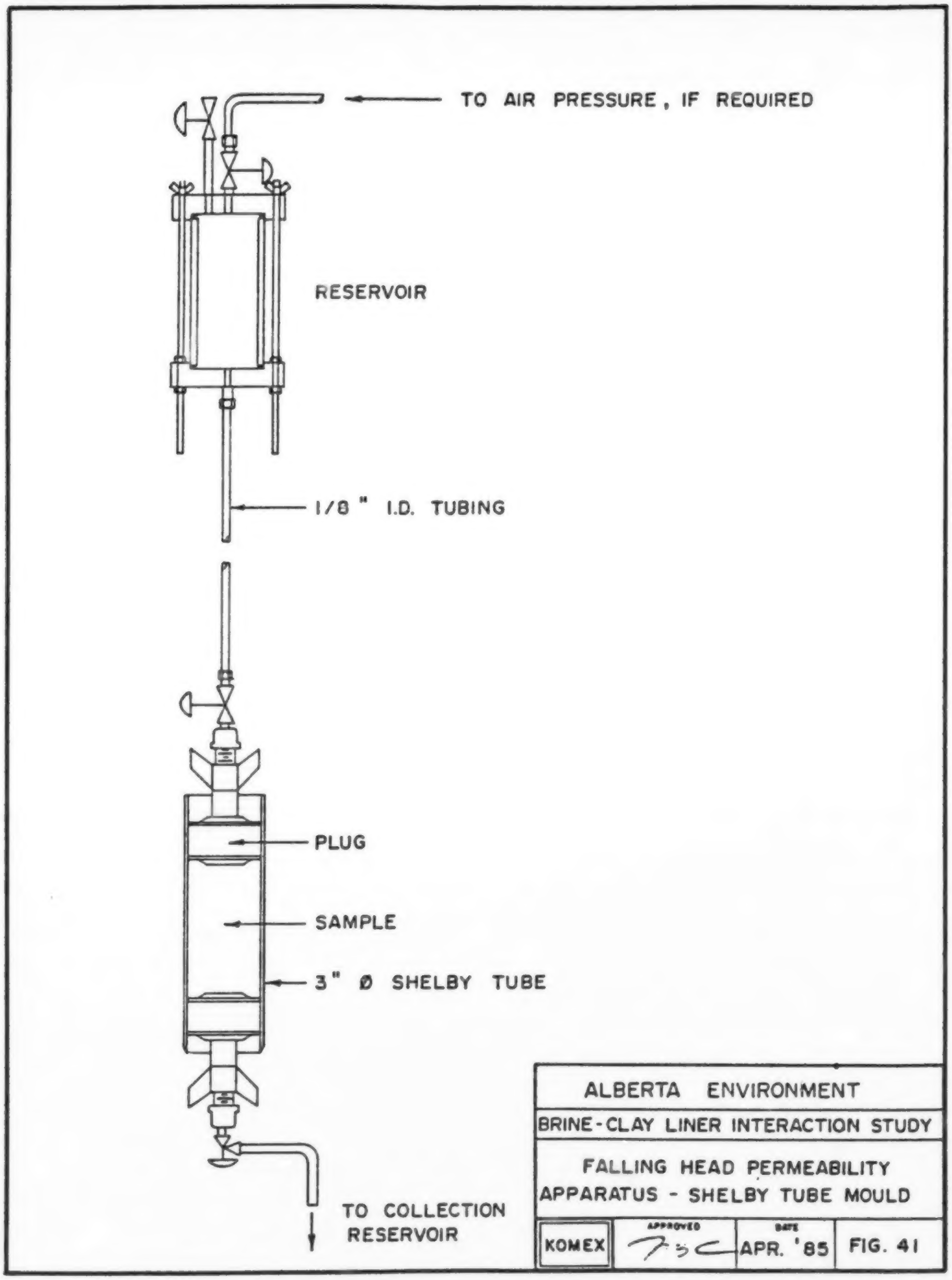


Figure 41. Falling head permeability apparatus - Shelby tube mould.

8.3.3.2 Compacted permeameter. The compacted permeameter cell and ends are completely manufactured out of acrylic plastic to the dimensions partially outlined in ASTM D698. The fittings and valves are brass. Rubber "O" rings provide for a seal between the cell and permeameter ends; the degree of seal achieved is controlled by six threaded clamp rods, as shown on the sketch and photograph in Figure 42.

The standpipes used were .3 cm opaque PVC tubes. Filter cloth separators were Fibretex 300 filter fabric, and the filter filler utilized was Sil 8 sand as indicated on Figure 43.

8.4 ANALYSIS OF EFFECTS OF BRINE ON TILL SAMPLES
(reported by AGAT Laboratories, Calgary)

8.4.1 Introduction

Two till samples were submitted by Komex Consultants for a study of effects of brine on clays. Only one sample was treated with brine, and an untreated fraction of this sample was not provided. Ideally, the study should have been performed on treated and untreated fractions of the same sample, or samples. The two samples provided differ both in texture and mineral composition. These two samples are thus treated separately, and effects of brine on clays are assessed on an individual sample basis. Clay minerals are present mainly in detrital forms, and exhibit undiagnostic morphology. Differentation of clay by quantitive analysis (energy-dispersive X-ray fluorescence, EDX) was hampered frequently by mineral contaminants (mainly feldspars and carbonates) in the proximity of clays analysed.

8.4.2 Sample #1 (Uncontaminated)

This sample is greyish brown, and is composed of clays and poorly sorted sand grains. The sample is unconsolidated, and breaks down readily in fresh water due to swelling of water-sensitive clays. The rate of breaking down is enhanced when 10% acid is applied, in part due to chemical reaction of acid with carbonates in the sample, particularly calcite. Sand grains vary

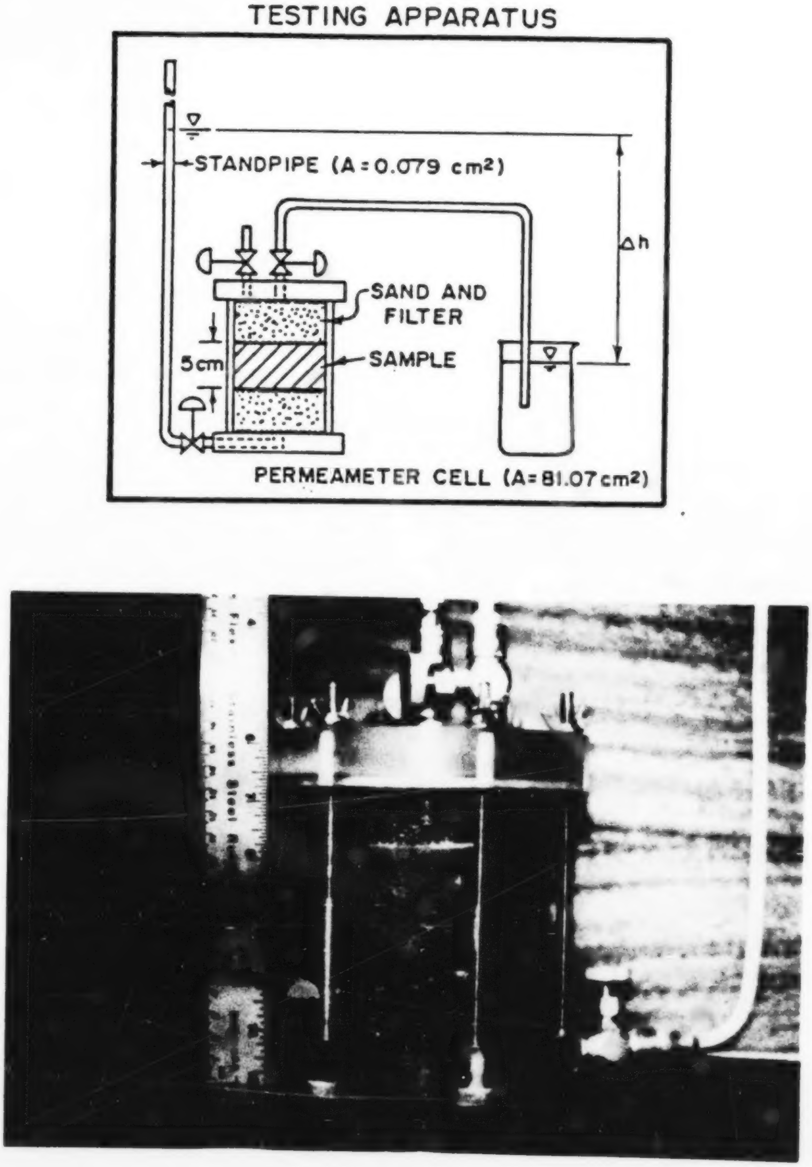
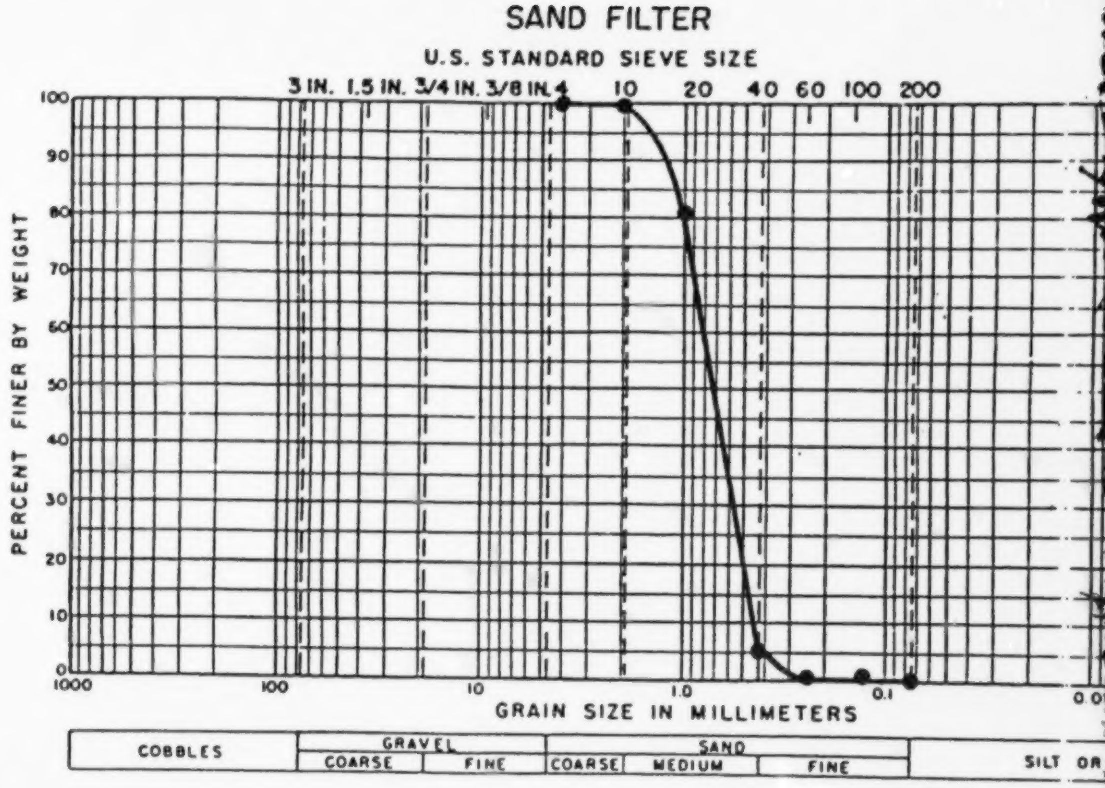


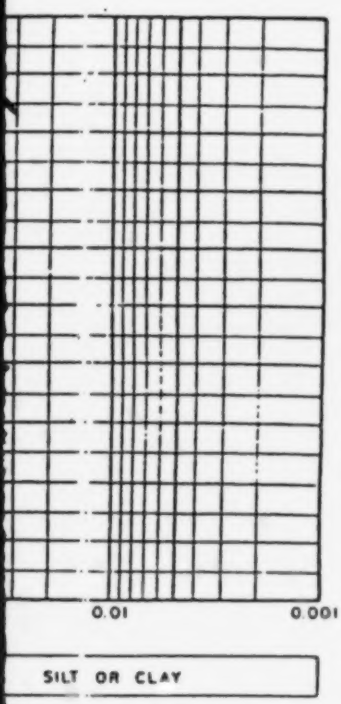
Figure 42. Falling head permeability apparatus - compaction mould.



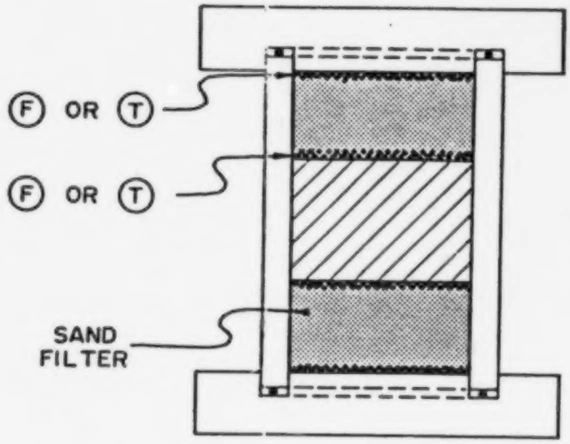
FILTER PROPERTIES

GEOTEXTILE FILTERS	THICKNESS	PERMEABILITY	EOS
Ⓕ FIBRETEX 300	90 mils	3×10^{-1} cm/sec	80-100 (U.S. STANDARD)
Ⓣ TERRAFIX 270 R	3.0 mm	2.6×10^{-1} cm/sec	130 (μm)

Figure 43. Filters used in permeability testing.



	MASS
ARD)	———
	270 g/m²



JOB No. 989

ALBERTA ENVIRONMENT

BRINE - CLAY LINER INTERACTION STUDY

FILTERS USED IN
PERMEABILITY TESTING

KOMEX	APPROVED	DATE	
	F B C	APR./85	FIG. 43

from rounded to subangular, and commonly are less than 1 mm in diameter. X-ray diffraction analysis of the sample incidates that its coarser portion is composed mainly of quartz and chert (54% of bulk sample, Table 23A) and feldspar (29%). Calcite and dolomite (3%, each) are probably present in part in detrital form.

Clays form 9% of the bulk composition, and are composed of smectite (4%), illite (3%), and kaolinite (2%). The relative amounts of these clay minerals in the clay-sized glycolated fraction (Table 23B) remain unaltered, thus suggesting the following:

1. that clay minerals occur in similar percentages in granular and finer "matrix" (less than 5 microns) forms, or
2. that clays are present in finer "matrix" form.

However, scanning electron microscope observations indicate that clay grains are also present, in addition to "matrix". Clay minerals in this sample may occur separately, but energy-dispervise X-ray fluorescence (EDX) analysis suggests that intermixing of clay is common. Clay minerals are present mainly in detrital form; however, well developed crystal form, observed on a local basis, suggests a degree of recrystallization or development of authigenic clays. Energy-dispersive X-ray fluorescence analysis of smectite in this sample indicates that it is in part of sodium-rich type, which attains a larger degree of intracrystalline expansion than Ca-rich smectite.

8.4.3 Sample #2 (Contaminated)

This sample is greyish brown, and is composed of moderately sorted sand grains with clays. It differs texturally from sample #1 in that it is finer-grained, and sand-size grains present are better sorted. This sample breaks down (but with a slower rate than sample #1) when in contact with fresh water, due to swelling of water-sensitive clays (mainly smectite); it also effervesces strongly due to the presence of carbonates (particularly calcite). X-ray diffraction analysis of a bulk sample indicates that

Table 23. Summary of X-ray diffraction analysis.[a] (Reported by AGAT Laboratories, Calgary)

A. Bulk Sample Analysis

Minerals	Sample #1	Sample #2[b]
Quartz	54	12
Plagioclase Feldspar	12	23
Potassic Feldspar	17	4
Amphibole	1	3
Calcite	3	4
Dolomite	3	4
Pyrite	1	3
Kaolinite	2	3
Illite	3	5
Mixed-layer clays[c]	ND	ND
Chlorite	Tr[d]	1
Smectite (Montmorillonite)	4	3

B. Glycolated Clay Fraction Analysis

MINERALS	Sample #1	Sample #2
Kaolinite	20	23
Illite	31	36
Mixed-layer clays	ND	ND
Chlorite	7	9
Smectite (Montmorillonite)	42	32

[a] Semi-quantitive data with ±10% accuracy.
[b] Sample contains NaCl.
[c] Commonly Illite and Smectite.
[d] Trace; detectable, but not measurable.

siliceous grains and fragments (quartz, chert, and silica-rich rocks) form 47% of the bulk composition, Table 23A), and plagioclase (23%) with a smaller amount of potassium feldspars (4%). Calcite and dolomite are present in equal proportions, and form 8% of the bulk composition.

Clays, forming 13% of the bulk composition (Table 23A), composed mainly of illite (5%), smectite (3%), kaolinite (3%), and chlorite (1%), are present mainly in detrital form. Variation in qualitative chemical analysis patterns (EDX) of mineral assemblages suggest various degrees of intermixing of clays. A drop in the amount of illite in the glycolated clay fraction (Table 23B) indicates that illite is present in part in detrital granular form. Clays, forming the finer-grained portion ("matrix") of the sample, rarely exhibit diagnostic morphology. The sample also contains NaCl (precipitate from brine) distributed irregularly as a thin film or as irregularly-shaped crystals.

8.4.4 Interpretation of Results

X-ray diffraction and energy-dispersive X-ray fluorescence analyses, and scanning electron observations of the uncontaminated and contaminated samples indicate the following:

- Clays are mainly detrital, rarely showing distinctive or diagnostic morphology.
- The type and quantity of clays (mainly smectite, illite, and kaolinite) are comparable in these two samples.
- Smectite in the uncontaminated sample (#1) is in part of Na-rich type which is highly expandable in fresh water medium; however, the larger portion of this clay mineral is of Ca-rich type.
- Smectite in the contaminated sample (#2) is mainly of Ca-rich type, which is less expandable than the Na-rich type.
- Sodium chloride have precipitated from brine as thin films or fine, irregularly-shaped crystals in Sample

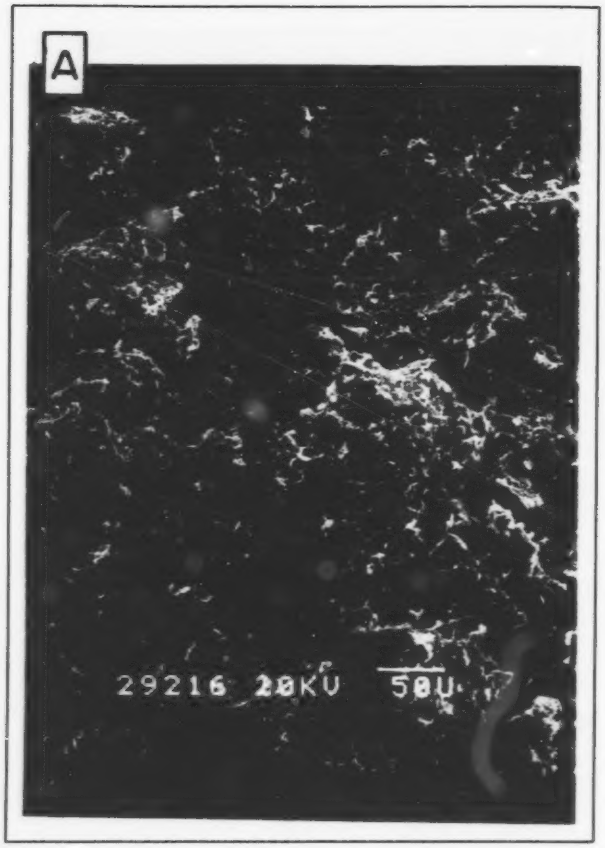
#2; EDX analyses suggest irregular distribution of this salt.

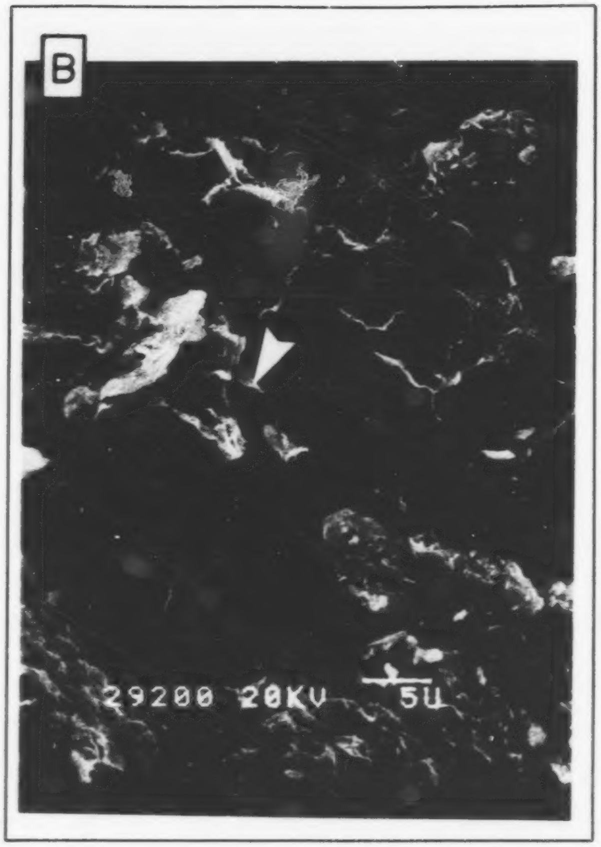
- Treatment with brine may have had a corrosive effect on clays, particularly in portions where sodium chloride is concentrated.
- Treatment of sample #2 with brine may have enriched smectite with sodium; however, EDX analysis of clay assemblages do not indicate significant enrichment.

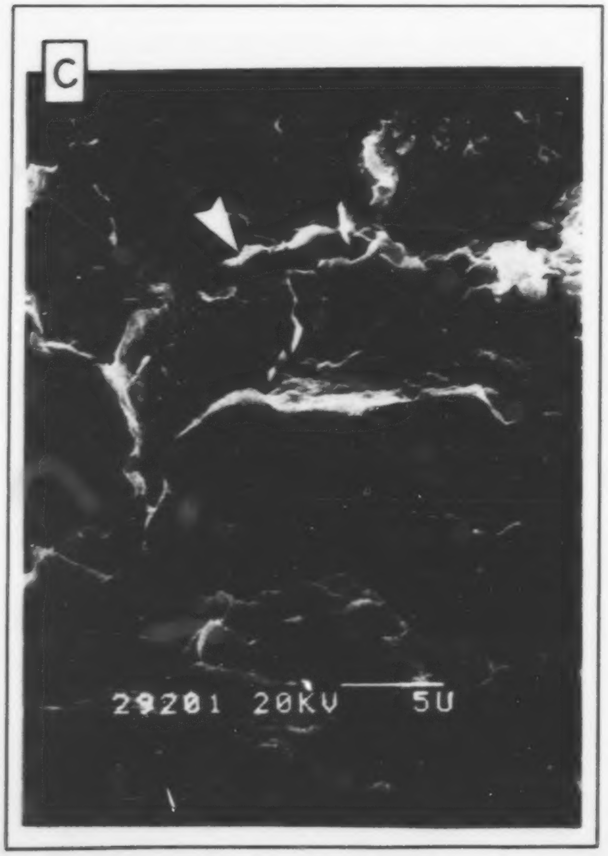
SEM PHOTOGRAPHS

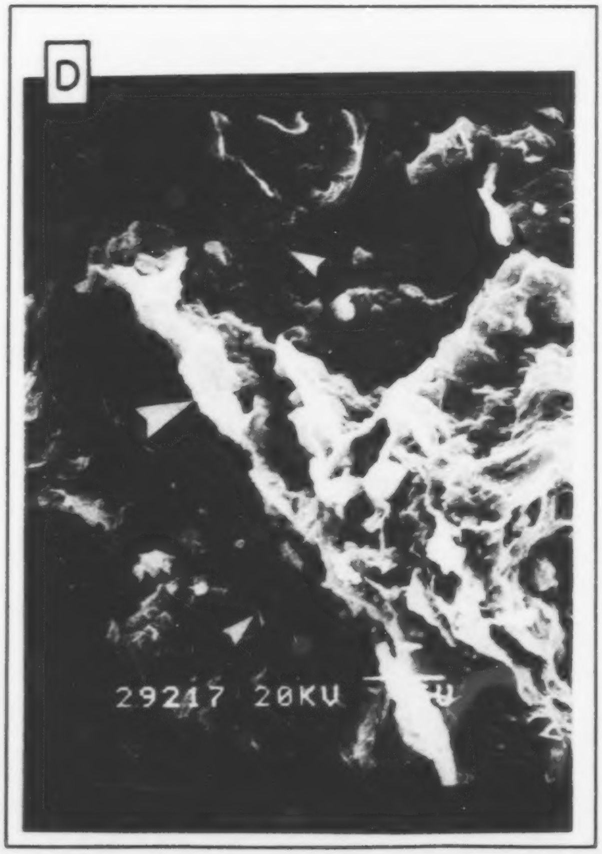
SAMPLE #1 (Uncontaminated)

A	A general view of a till sample with poorly sorted sand grains composed mainly of quartz, chert, and feldspars; clays (mainly smectite, illite, and kaolinite) form a significant part of the sample. Magnification of 250 times.
B + C	Two fields of view showing crenulated clays (mainly illite and smectite). Energy-dispersive X-ray fluorescence analysis of different points yielded composition dominated by Si, Al, K, Ca, Na, Mg, and Fe suggesting significant intermixing of clay minerals. Crystal morphology of clay present is not diagnostic of particular clay types; however, relatively well developed crystal form suggests a certain degree of recrystallization, or formation of authigenic clays. Note the undisturbed sharp and "clean" edges of clay platelets (arrows). Magnification of B is 2600 times and of C is 4000 times.
D	Detail of clays, in this case identified individually as smectite (large arrow) and illite (small arrows). Magnification of 3100 times.


A
29216 20KV 50U


B
29200 20KV 5U


C
29201 20KV 5U


D
29217 20KV U

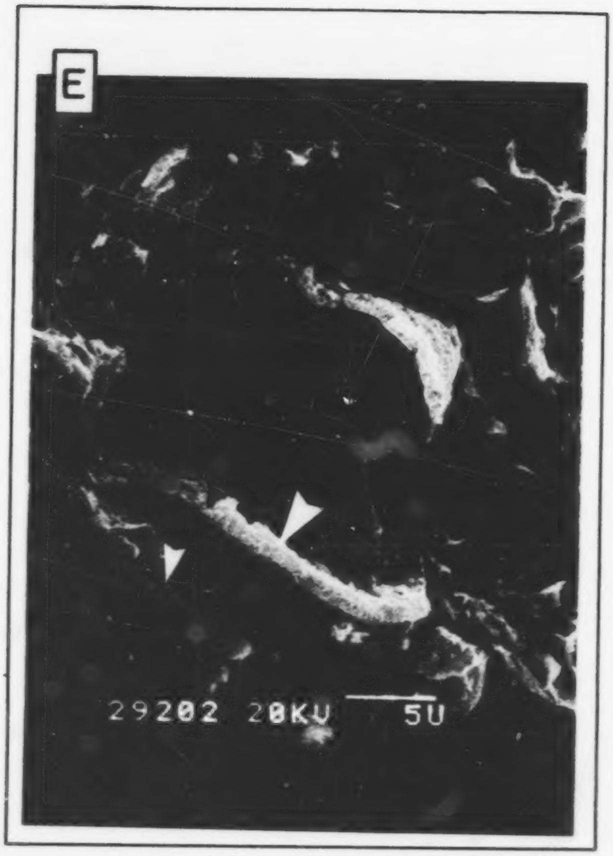
SEM PHOTOGRAPHS

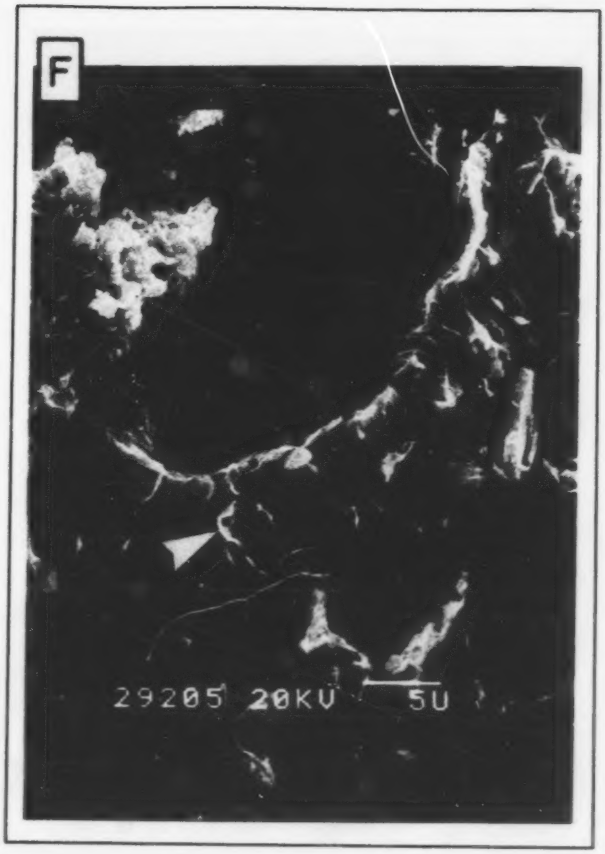
SAMPLE #1 (Uncontaminated)

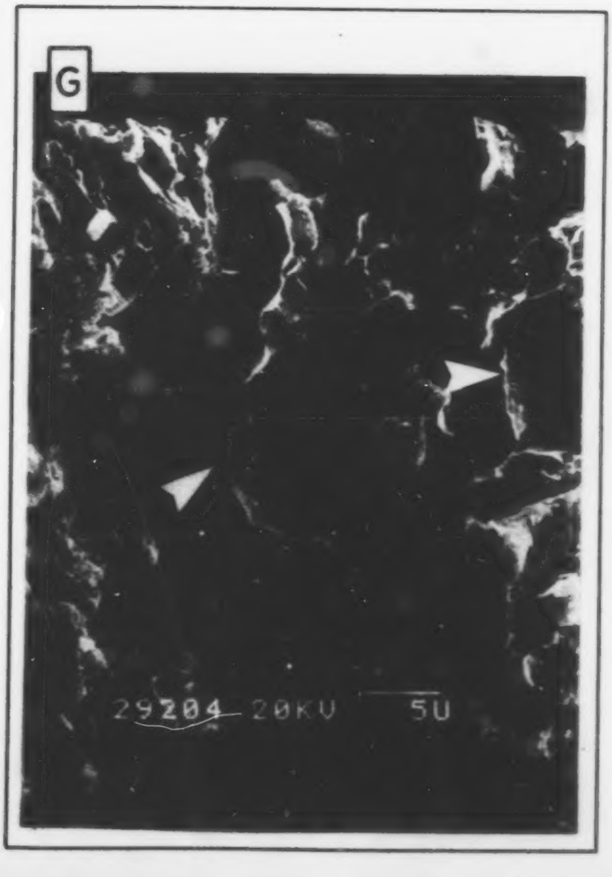
E This field view shows the presentce of intermixed clays, mainly smectite and illite. Energy-dispersive X-ray fluorescence analysis of different points on clays; however, suggests the presence of a sodium-rich type smectite (large arrow), and a calcium-rich type smectite (small arrow). Note that the former (large arrow) probably exhibits a degree of swelling. Magnification of 3500 times.

F View showing detail of mainly illitic clay with thin platy projections (arrow). Magnification of 300 times.

G Detail of intermixed clays, mainly smectite and illite. Note that platelets are fused at their ends, and that platelets edges are sharp and undisrupted (arrows). Magnification of 3100 times.


E
29202 20KV 5U

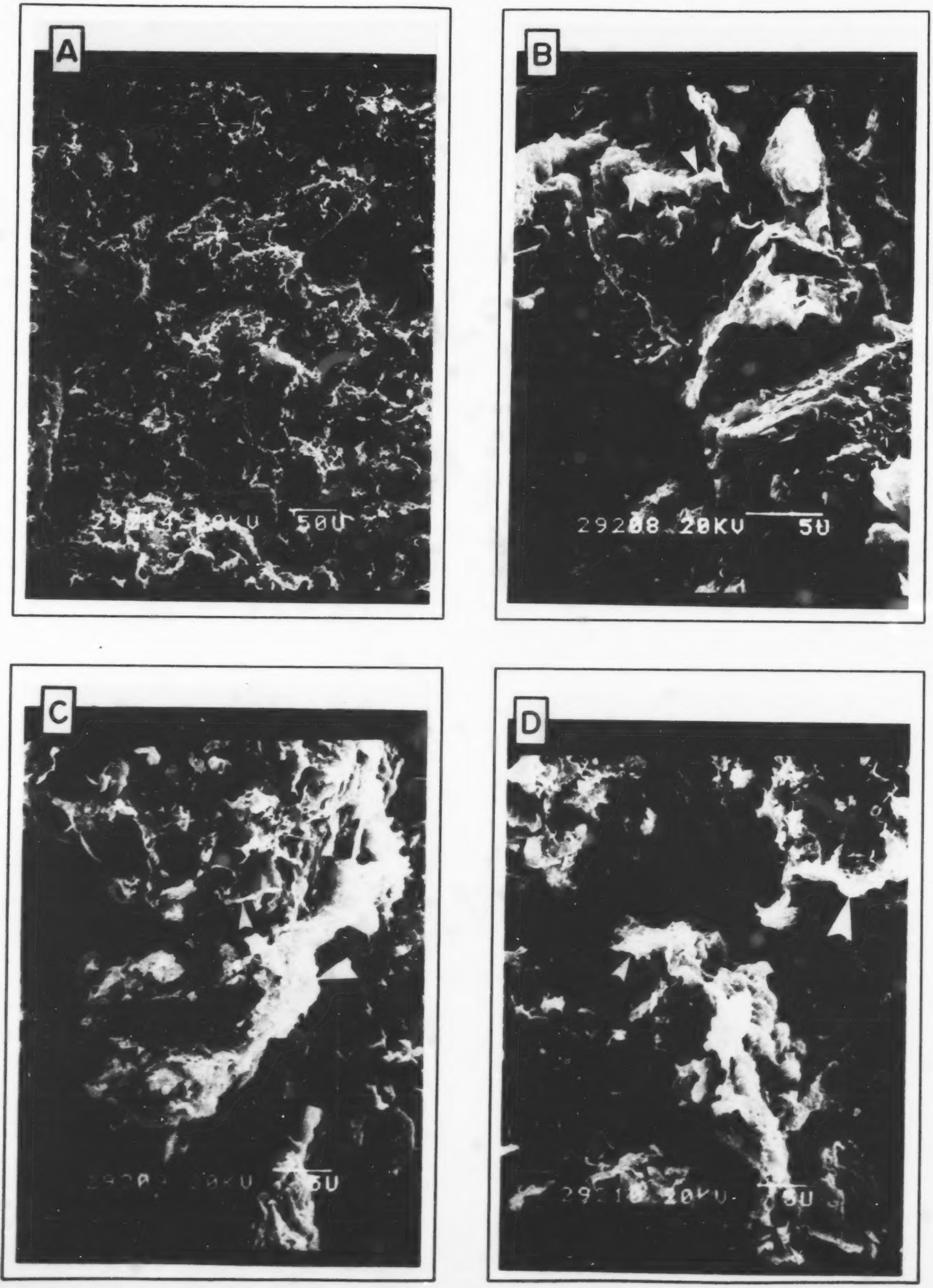

F
29205 20KV 5U


G
29204 20KV 5U

SEM PHOTOGRAPHS

SAMPLE #2 (Contaminated)

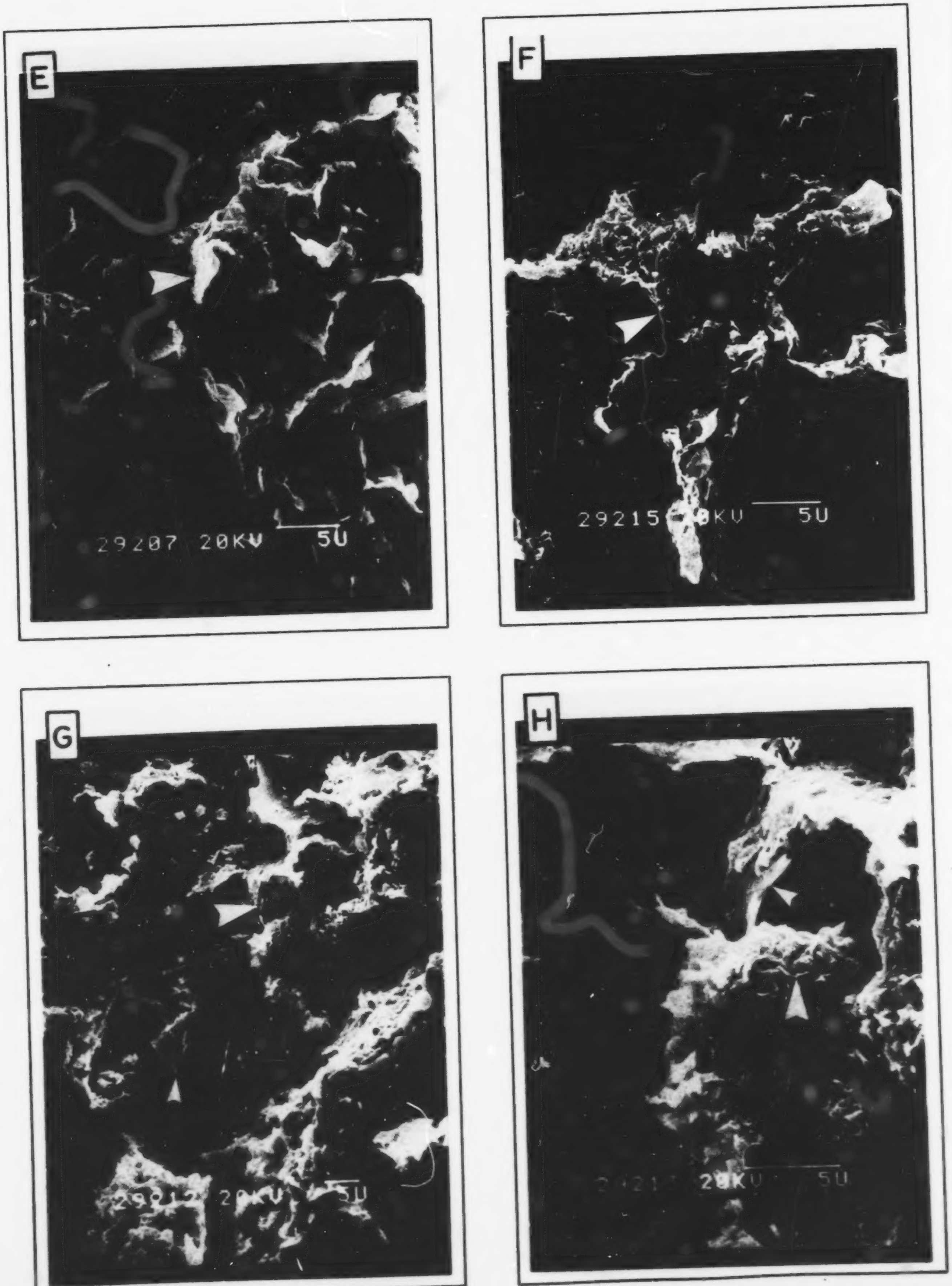
A	An overview of a till sample composed of poorly sorted sand and silt grains (mainly quartz, chert, and feldspars) and clays (mainly illite and kaolinite). Magnification of 250 times.
B to D	Three fields of view showing mixtures of clays, mainly illitic (small arrows) and smectite (large arrows). Intermixing of clays is indicated by complex and variable chemical composition, as indicated by energy-dispersive X-ray fluorescence analyses. Crystal morphology of clays is comparable with that observed in sample #1. Although platelet corrosion is not evident in these fields of view, edges appear corroded locally around sodium chloride crystals. Magnification of B is 4000 times, of C is 3000 times and of D is 2500 times.


A
50U
B
29208 20KV 5U
C
D

SEM PHOTOGRAPHS

SAMPLE #2 (Contaminated)

E + F	Two fields of view showing illite (arrow in E) and smectite (arrow in F) indicates a composition dominated by Si, Al, Ca, Mg, and Fe, with minor K. There is no indication that clay platelets have been corroded to any significant degree in these field of view. Magnification is 3600 times.
G	Detail of clays, largely smectite in composition (large arrow), exhibiting a high degree of open space-bridging. A small cluster of clay (indicated by a small arrow) is probably broken during sample preparation, and does not represent a collapse structure. Magnification is 1800 times.
H	Part of photograph G magnified to show a cluster of illitic clay (large arrow) and smectite (small arrow). It is not clear whether these clay assemblages have suffered any significant corrosion. Corrosion is more evident in other parts of the sample where sodium chloride crystals are present; however, it does not appear to have occurred on a large scale. Magnification is 5000 times.

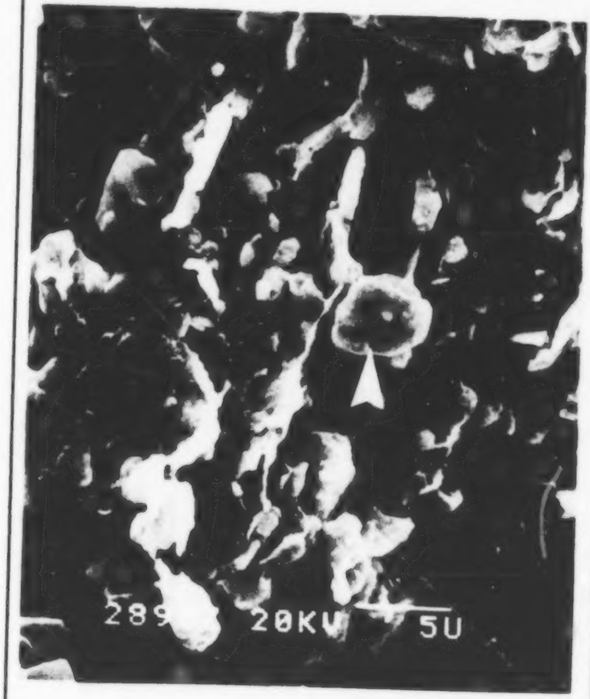

E
29207 20KV 5U
F
29215 20KV 5U
G
29212 20KV 5U
H
29213 20KV 5U

SEM PHOTOGRAPHS

A + B	Two fields of view showing detrital clays (mainly illitic in A, and illitic and chloritic in B). Energy-dispersive analysis indicates that minor NaCl is present in the field in view in A, but that a significant amount of salt is present in the field of view shown in B (arrow). Note the similarity in clay microfabrics in the two photographs. Magnification of A is 3100 times and of B is 3500 times.
C	An aggregate of illitic clay (large white arrow) surrounded by abundant salt coatings (small white arrows). Note that thin clay platelets on the aggregate surface appear undisturbed (black arrows). Magnification is 1700 times.
D	Detail of clay showing apparent collapse (arrows). This structure may be a result of treatment or may have resulted from compaction. Magnification is 5000 times.

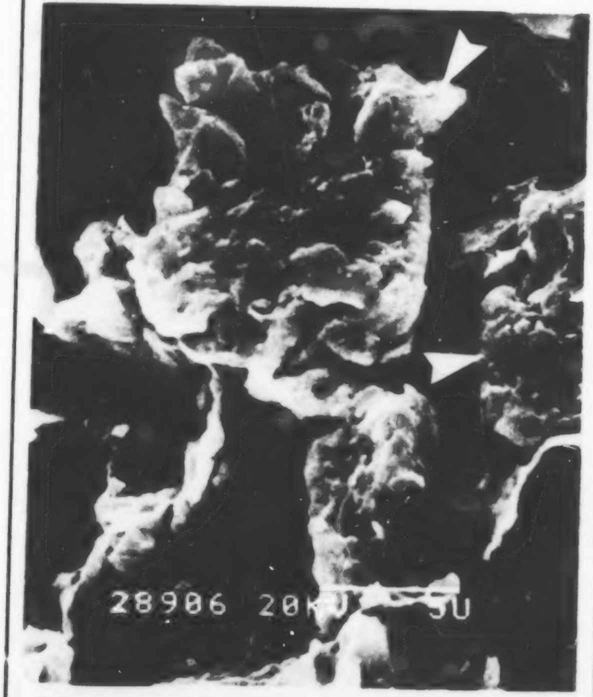
A

B



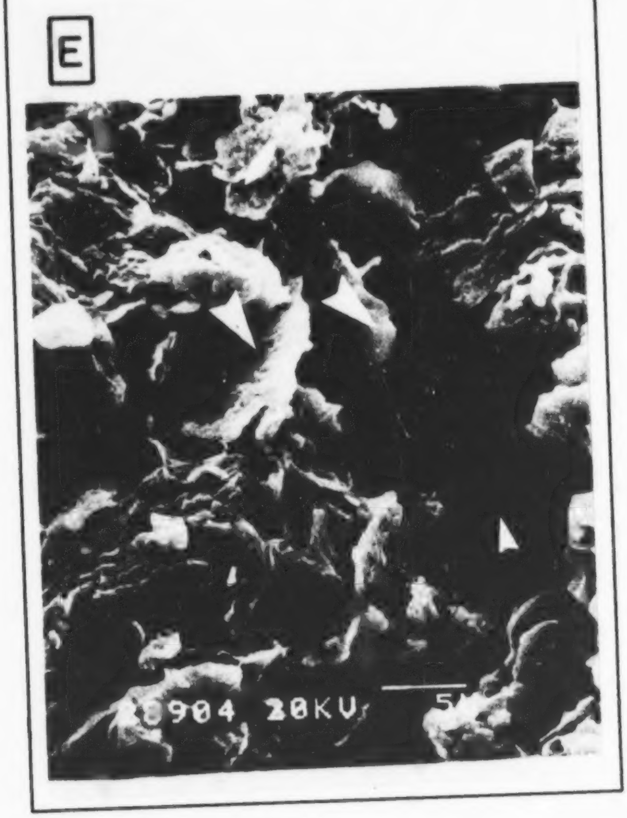
C

D



SEM PHOTOGRAPHS

E This field of view shows the detail of crude clay platelet alignment (large arrows); it is not clear whether this is a natural occurrence or due to brine treatment, or compaction. Note, however, the presence of a clean surface (small arrow) which is free from clays. This probably is another indication of brine effect. Magnification is 3100 times.


E
904 20KV
5

8.5 CHEMICAL ANALYSES OF SOIL AND BRINE PERMEANT

8.5.1 Introduction

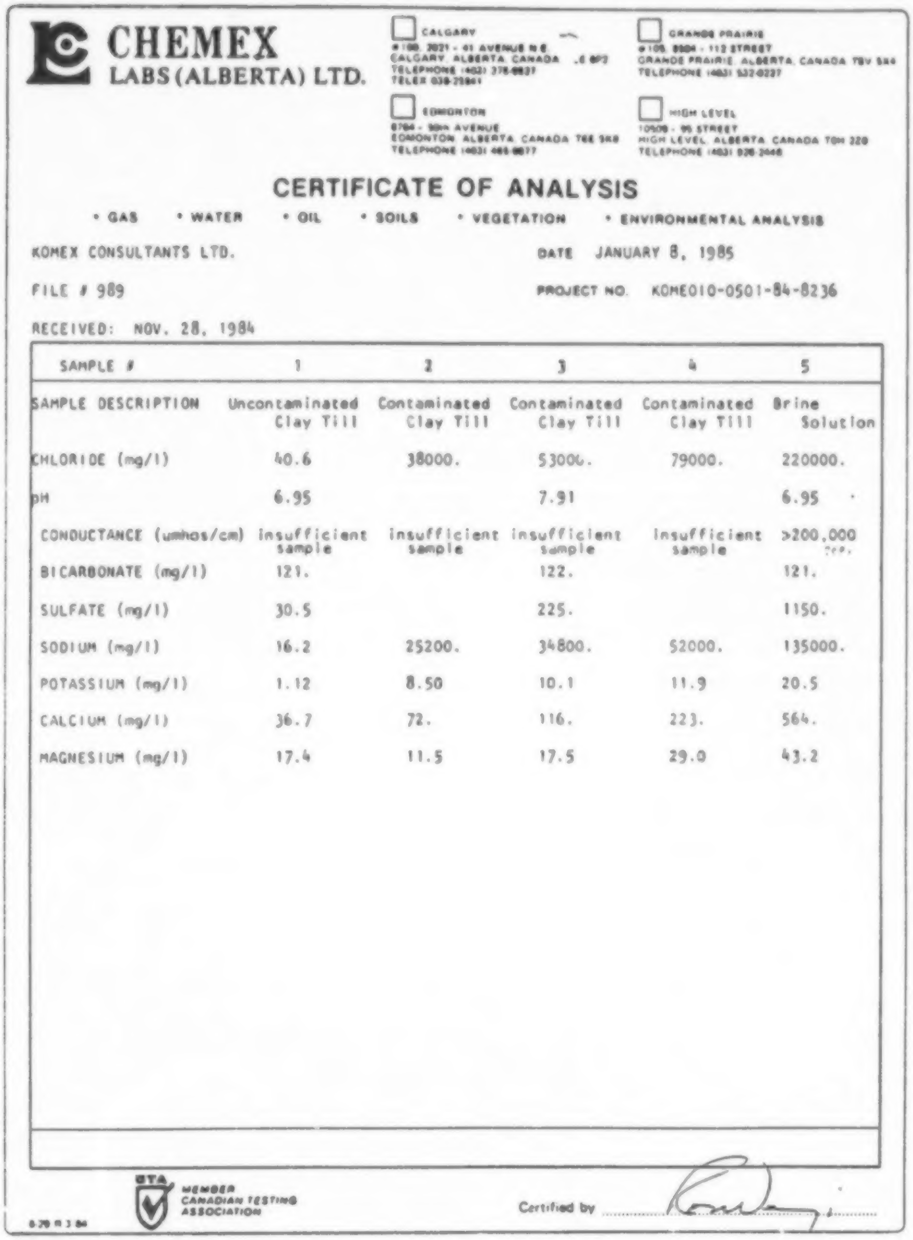
The chemical analyses of soil and brine permeant were prepared for Komex by Chemex Labs (Alberta) Ltd. The methods of analysis used at Chemex for the samples are as follows. The soil reaction or pH was determined on a saturated paste and the electrical conductivity on a saturated paste extract. The sodium and potassium levels were also determined from this extract and were measured by flame photometry. Calcium and magnesium were determined from the extract by atomic adsorption spectroscopy. The carbonate/bicarbonate levels were determined by titration with 0.04 N HCl to pH values of 8.3 and 4.5, respectively. Chloride and sulphates were determined by ion chromotography.

These methods are explained in greater detail in:

McKeague, J.A., Ed. 1978. Manual on soil sampling and methods of analysis. Second Edition. Prepared by the Subcommittee on Methods of Analysis of the Canada Soil Survey Committee for the Canadian Society of Soil Science. Ottawa. 212 pp.; and.

Franson, M.A.H., A.E. Greenberg, J.J. Connors, and D. Jenkins. 1980. Standard methods for the examination of water and wastewater. Fifteenth Edition. Prepared and Published Jointly by the American Public Health Association, American Water Works Association, and Water Pollution Control Federation. Washington, D.C. 1134 pp.

Table 24. Chemical analyses of soil and brine permeant.



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☐ EDMONTON
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☐ HIGH LEVEL
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CERTIFICATE OF ANALYSIS

• GAS • WATER • OIL • SOILS • VEGETATION • ENVIRONMENTAL ANALYSIS

KOMEX CONSULTANTS LTD.

DATE JANUARY 8, 1985

FILE # 989

PROJECT NO. KOME010-0501-84-8236

RECEIVED: NOV. 28, 1984

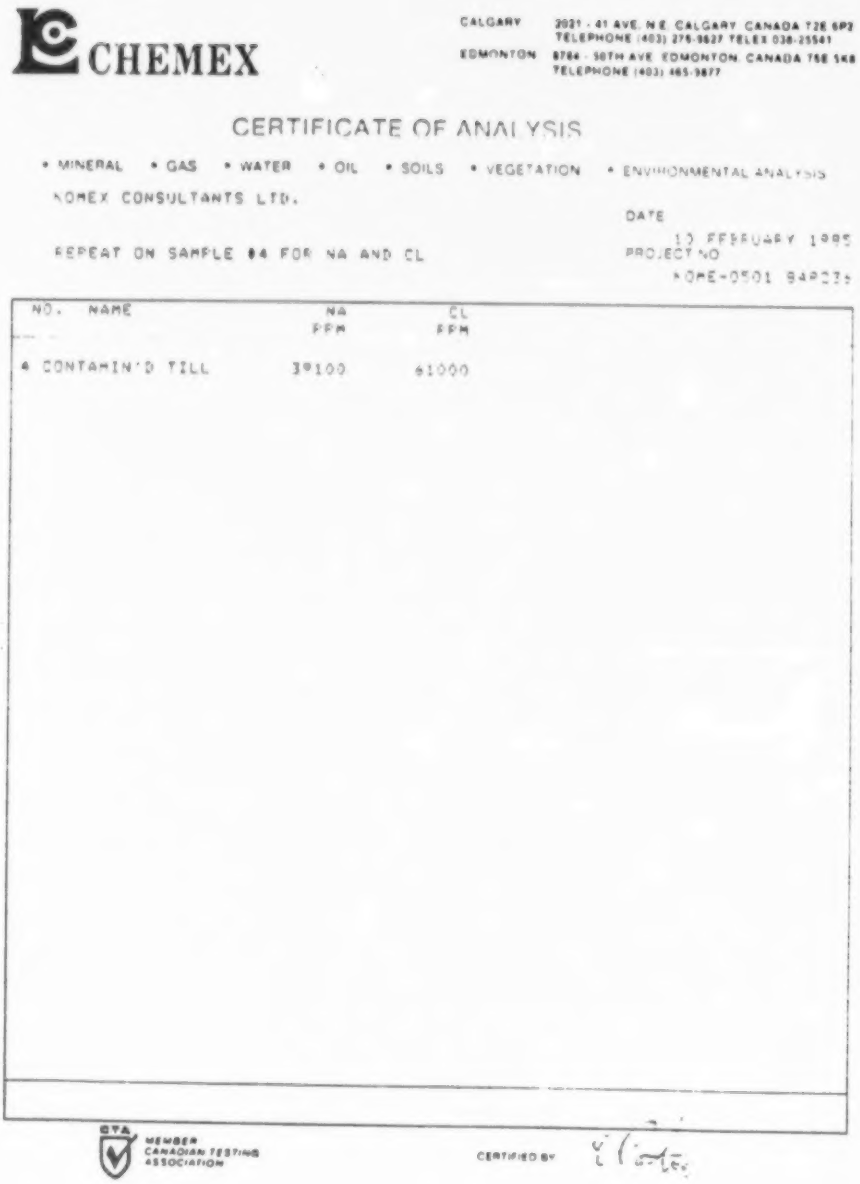
SAMPLE #	1	2	3	4	5
SAMPLE DESCRIPTION	Uncontaminated Clay Till	Contaminated Clay Till	Contaminated Clay Till	Contaminated Clay Till	Brine Solution
CHLORIDE (mg/l)	40.6	38000.	53000.	79000.	220000.
pH	6.95		7.91		6.95
CONDUCTANCE (umhos/cm)	insufficient sample	insufficient sample	insufficient sample	insufficient sample	>200,000
BICARBONATE (mg/l)	121.		122.		121.
SULFATE (mg/l)	30.5		225.		1150.
SODIUM (mg/l)	16.2	25200.	34800.	52000.	135000.
POTASSIUM (mg/l)	1.12	8.50	10.1	11.9	20.5
CALCIUM (mg/l)	36.7	72.	116.	223.	564.
MAGNESIUM (mg/l)	17.4	11.5	17.5	29.0	43.2

CTA MEMBER CANADIAN TESTING ASSOCIATION

Certified by ....

continued . . .

Table 24. Concluded.



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TELEPHONE (403) 465-9877

CERTIFICATE OF ANALYSIS

• MINERAL • GAS • WATER • OIL • SOILS • VEGETATION • ENVIRONMENTAL ANALYSIS

KOMEX CONSULTANTS LTD.

DATE
10 FEBRUARY 1985
PROJECT NO
KOME-0501 84P235

REPEAT ON SAMPLE #4 FOR NA AND CL

NO.	NAME	NA PPM	CL PPM
4	CONTAMIN'D TILL	38100	61000

CTA MEMBER CANADIAN TESTING ASSOCIATION

CERTIFIED BY

Table 25. Water examination report - monthly mean - Glenmore effluent.

Tests - mg/L (or as noted)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
PHYSICAL PROPERTIES												
Turbidity (N.T.U.)	0.38	0.36	0.47	0.37	0.46	0.34	0.47	0.34	0.37	0.33	0.31	0.35
Color Units	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
pH (pH Units)	8.13	8.14	8.26	8.11	8.10	8.20	8.26	8.31	8.22	8.29	8.33	8.15
Hardness, as $CaCO_3$ E.D.T.A.	244	240	237	217	186	174	172	168	177	190	203	224
Conductivity (Microsiemens/cm)	422	428	432	410	351	322	281	290	314	334	366	392
Temperature (°C)	2.5	2.1	2.0	3.7	8.7	14.6	16.8	19.5	14.7	8.9	5.1	2.3
Total Dissolved Solids, Calcd.	264	279	273	259	219	190	192	190	202	217	229	246
Saturation Index, Calcd.	+0.17	+0.19	+0.17	+0.10	+0.07	+0.29	+0.40	+0.49	+0.34	+0.29	+0.30	+0.13
INORGANIC NON-METALS												
Total Alkalinity, as $CaCO_3$	188	187	177	160	137	125	126	122	127	136	146	160
Carbonate	0	0	0	0	0	0	0	1	0	0.2	0.9	0
Bicarbonate	229	227	215	194	165	152	154	146	155	165	177	195
Chlorine Residual, Free	0.40	0.40	0.40	0.37	0.35	0.35	0.35	0.36	0.38	0.44	0.45	0.45
Chlorine Demand, Calcd.	-	-	-	-	-	-	-	-	-	-	-	-
Fluoride	0.26	0.26	0.25	0.22	0.22	0.23	0.25	0.17	0.21	0.22	0.21	0.22
Chloride	2.8	2.9	3.7	5.7	4.0	2.2	2.2	2.2	2.3	2.2	2.2	1.8
Nitrite	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1
Phosphate, Orthe	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1
Bromide	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1
Nitrate	0.38	<0.48	0.39	0.42	<0.24	<0.13	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1
Sulphate	62	72	75	74	63	47	49	50	54	60	61	64
Ammonium	0.07	<0.05	<0.02	<0.02	<0.03	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Silica*	4.8	4.4	4.3	3.6	4.0	4.0	4.0	4.4	4.4	3.9	3.9	4.1

continued . . .

Table 25. Continued.

Tests - ug/L (or as noted)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
METALS												
Aluminum												
Barium					<100			<200		114	86	114
Cadmium	<5			<5	<5			<0.1		<0.1	<0.1	<0.1
Calcium (mg/L)	60	64	62	58	49	46	45	44	47	50	55	60
Chromium	<20			<20	<20			<20				<0.1
Copper	<20			<20	<20			6		6	5	6
Iron	37			<10	<10			22	19			24
Lead				<0.5	<1.0			<0.5				<0.05
Magnesium (mg/L)	17	19	17	16	13	13	13	15	16	16	17	17
Mercury								<0.2				<0.2
Nickel								<1.0				<1.0
Potassium (mg/l)	0.76	0.75	0.79	0.94	1.05	0.55	0.61	0.51	0.54	0.66	0.75	0.86
Selenium								<1.0				<0.5
Silver								<5				<0.1
Sodium (mg/L)	3.2	3.1	3.5	4.7	3.6	1.9	2.0	2.0	2.3	2.5	2.5	2.5
Strontium (mg/l)	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Zinc	<5			<5	<5			<0.1				
TOXIC ELEMENTS												
Cyanide*								<2			<2	
Arsenic								<0.1				<0.1

continued . . .

Table 25. Concluded.

Tests - mg/L (or as noted)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
ORGANICS												
Chemical Oxygen Demand	< 5.0(a)		4	5.2(a)				6.5(a)	<1	2.8		4.8
Dissolved Organic Carbon (a)	< 0.4			0.8				0.9				0.8
Dissolved Inorganic Carbon (a)	44.0			35.0				30.0				41.0
Chloroform (ug/l)			9.04	5.05		29.34						
MICROBIOLOGICAL												
Standard Plate Count/1 mL **	1.6	2.4	5.9	2.4	2.7	<0.6	<0.8	<0.8	<0.9	<0.9	<0.6	0.9
MF Total Coliform/100 mL	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.24	<0.21
MF Fecal Coliform/100 mL	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.24	<0.21
MF Fecal Streptococcus cfu/100 mL	N.T.	N.T.	N.T.	N.T.	N.T.	N.T.	N.T.	N.T.	N.T.	N.T.	N.T.	N.T.

Test Results: * - Single Sample ** - Geometric Mean (a) Alberta Environment MF - Membrane Filtration N.T. = Not Tested